

Urban Waterfront Rehabilitation In Pelluhue County, Chile

Affected by the Chile 2010 Earthquake and Tsunami

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Abstract

During the morning of February 27th, 2010, a strong earthquake with a magnitude of 8.8Mw affected the central region of Chile. As a result of the earthquake, tsunami waves were generated. These waves hit the coastal towns with great intensity in the central region of Chile, from Valparaiso to Tirua. The main economical activities: fishing, tourism, and other forms of local commerce, were seriously affected due to the destruction of the earthquake and tsunami.

Pelluhue County is located in the southwest zone of the VII region, the central zone of Chile, which is part of Cauquenes' province local government. Its coastline is lies along the Pacific Ocean. In this county, the damage was mostly concentrated along the waterfront, having a great degree of destruction up into the river mouths. In this thesis the flood destruction is analyzed in the urban waterfront of Curanipe, Pelluhue, and Mariscadero. The damage generated by the tsunami flood illustrates the high degree of exposure of buildings and structures abutting Pelluhue's waterfront. The nonexistence of any mitigation elements allowed the direct impact of tsunami waves against dwellings. Compounding the issue, the lack of an evacuation plan increased the number of victims in the county.

The effectiveness of the most common artificial coastal defensive structures is evaluated in different tsunami scenarios. By analyzing the performance of these systems, it is clear that the forces of nature are stronger than any structure trying to contain them. This thesis explores the integration of a tsunami forest in the waterfront, which helps to consolidate the existing dune barrier. In this way natural-mitigation barriers are incorporated in the waterfront and riverfront, which not only play a defensive role, but also create a natural environment that support tourism, and incorporates an educative program along the circulation paths through the forest and dune barrier.

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Introduction

Based on the destruction, which occurred during the earthquake and tsunami of Chile in 2010, this thesis work is focused in the rehabilitation of a significantly impacted coastline in Pelluhue County. Located along the coast of the central region of Chile, next to the epicenter of the earthquake, this area was strongly affected by the earthquake and tsunami destruction. In this county, as well as in most of the towns located along the coast, the tsunami flood affected several dwellings, public buildings, and public infrastructure.

Pelluhue County is located in the southwest zone of the VII region, the central zone of Chile, being part of Cauquenes' province local government. Its coastline faces the Pacific Ocean. In this county, the damage was mostly concentrated along the waterfront, with a great degree of destruction occurring up into the river mouths. Before the tsunami, the waterfront and riverfront, were densely inhabited by people mainly linked to the traditional coastal occupations who ignore the threat involved in being located next to the river mouths. The nonexistence of mitigation elements allowed the direct impact of tsunami waves against dwellings. At the same time, the lack of an evacuation plan increased the number of victims in the county.

This thesis investigates flood destruction in the urban waterfront of Curanipe, Pelluhue, and Mariscadero from a structural and geographic approach. The flood, resulting from the tsunami, produced a high degree of damage in buildings and structures placed along the Pelluhue waterfront. In order to explore the conventional strategies and structures used to protect the population against tsunami waves, the effectiveness of the most common artificial coastal defensive structures were evaluated in various tsunami scenarios. This analysis indicates that the forces of nature are stronger than any structure trying to contain them. From the case studies analyzed, it is evident that the best measure to protect people is the evacuation of the coastal zones. Furthermore, trying to implement coastal structures resistant to tsunami flooding is ineffective during big tsunamis.

In order to define the future interventions to support the development of the local economy as well as improve the quality of life in Pelluhue County, this thesis researches the economic and cultural potentialities of the county. By analyzing the activities that take and have taken place in the waterfront of Pelluhue, it is possible to project the growth of the county based supporting the historic activities and adding more security to the coastal operations. At the same time, the great educational potential of the waterfront is recognized, where it is possible to educate the local people about the conscious use of natural resources available in Pelluhue County, and the tourists about the local ecosystem and natural disasters.

Due to the lack of economic resources needed to build large-scale defensive structures against tsunamis, the tsunami forests and dune barriers are a realistic solution for Pelluhue County based on the generation of favorable conditions and low costs of implementation. Based on the data obtained in this research, a preliminary schematic design is developed in Pelluhue town, in order to visualize how a defensive green belt can take form in the coasts of Pelluhue town, which experienced partial destruction during the 2010 tsunami, due to the lack of tsunami mitigation works.

Chapter I: Geography and Natural Disasters in Chile.

A. Geography of Chile

1. General Geography of Chile

The geography of Chile possesses great diversity as it stretches from the latitude 17° South to Cape Horn at 56°. The territory is a narrow strip of land, from the ocean on the west side to the Andes mountains in the east. Chile is situated in the southern region of South America, bordering the South Pacific Ocean and a small part of the South Atlantic Ocean.



Figure 1: Chile in South America
Source: Felipe Iguait

Chile extends 4,270 km (2,653 mi) from north to south, and averages 177 km (110 mi) east to west. Chile's northern neighbors are Peru and Bolivia, and borders Argentina to the east, at 5,150 km (3,200 mi), is the world's third longest. The Chilean coastline reaches 6,435 km (4,000 mi).¹

¹ "Country Nuclear Power Profiles," last modified July 20, 2013,
<http://www.pub.iaea.org/MTCD/Publications/PDF/cnpp2014cd/countryprofiles/Chile/Chile.htm>

The northern two-thirds of Chile lie on top of the telluric Nazca Plate. This plate is currently moving eastward about ten centimeters per year, forcing its way under the continental plate of South America. As a result of this movement, the Peru-Chile Trench is formed. The trench is about 150 km (93 mi) wide and averages about 5,000 m (16,404 ft) in depth. This clashing process between the Earth's surface plates also generates the Andes. The Andes are a geologically young mountain range; within Chile alone it includes about 620 volcanoes, many of them active.²



Figure 2: Chile's tectonic setting.
Source: Air Worldwide³

² "Geography of Chile," last modified March 27, 2013, <http://countrystudies.us/chile/36.htm>

³ "Earthquake Risk in Chile after February 2010," last modified August 16, 2010, <http://www.air-worldwide.com/Publications/AIR-Currents/2010/Earthquake-Risk-in-Chile-after-February-2010/>

About 80 percent of the land in Chile is made up of mountains with extremely diverse shapes, colors and sizes, depending of the latitude. Most Chileans live near or in this hilly territory, especially in the plain area defined between the coastal range and the Andes Mountains. The Non-Andean Mountains usually form part of transverse and coastal ranges. This special geographical arrangement creates several very productive valleys from north to south, especially in the central zone of Chile. All of these valleys have an east-west directional orientation. In the far south, the valleys run into the ocean's waters. The higher elevations of the coastal range facing the Andes in the far south become a multiplicity of islands, forming a complex labyrinth of channels and fjords.

Most of Chile's coastline is rugged. The Humboldt Current, which originates northwest of the Antarctic Peninsula, runs the full length of the Chilean coastline, making the water frigid. In Chile's beaches, located in the central part of the country, the water gets no warmer than 15 °C (59 °F) during summer. Toward the north, in Iquique, the water's temperature can reach the 18.1°C / 64.5°F. In the south, in Puerto Cisnes, the water temperature is usually 8.6°C / 47.4°F.⁴

⁴ "World Sea Temperatures," last modified September 20, 2013, <http://www.seatemperature.org/>

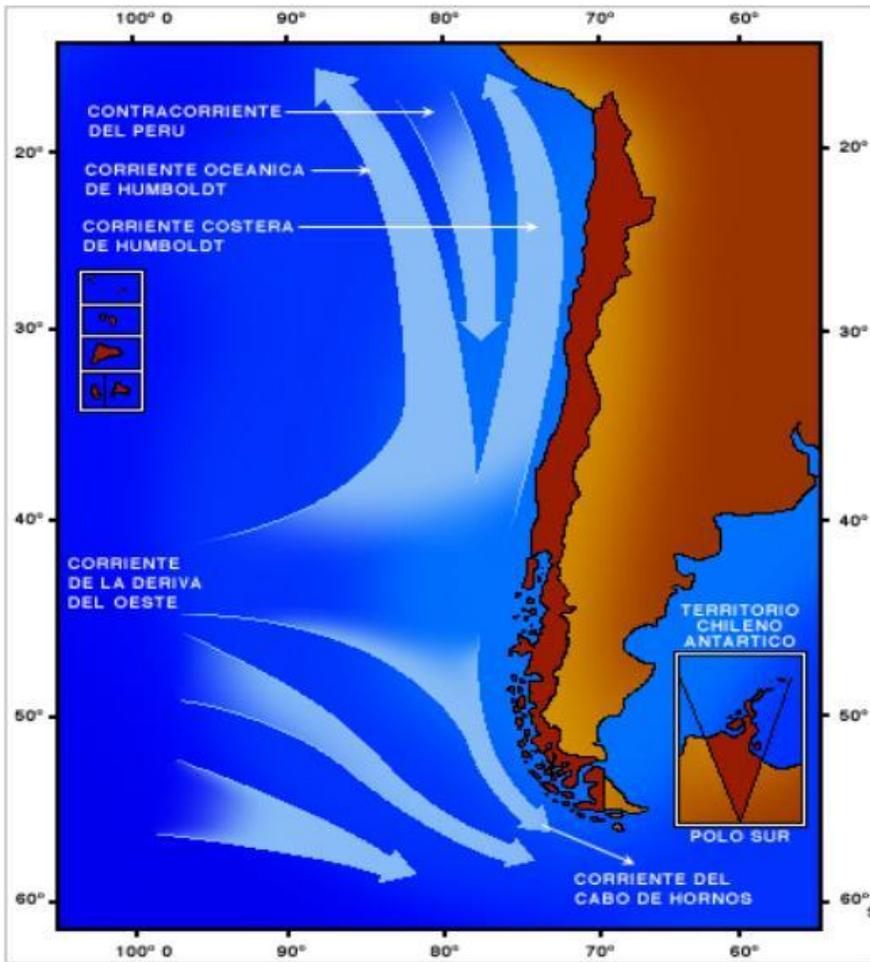


Figure 3: Chile's Humboldt Current.
 Source: *Escuela de Ingeniería de Antioquia*⁵

2. Central Zone of Chile

Geographers usually divide the Chilean territory into five main regions: the far north, the near north, central Chile, the south, and the far south. Each of these regions has its characteristic flora and fauna, climate, and special topographical characteristics.

Central Chile is the region where the majority of the population resides, including the three largest metropolitan areas: Santiago, Valparaíso, and Concepción. It extends from

⁵ "Corriente de Humboldt," last modified September 25, 2013, <http://fluidos.eia.edu.co/hidraulica/articulos/interesantes/humboldt/humboldt.htm>

about 32° south latitude to about 37° south latitude. The climate is of the Temperate Mediterranean type, with the amount of rainfall increasing considerably and progressively from north to south.

The diverse topography of central Chile includes a Coastal range of mountains running parallel to the Andes range. Placed in between the two mountain ranges is the so-called Central Valley, which contains some of the most productive agricultural land in the country. The areas to the north and south of Santiago are the largest producers of fruits, including the grapes from which the best Chilean wines are made.

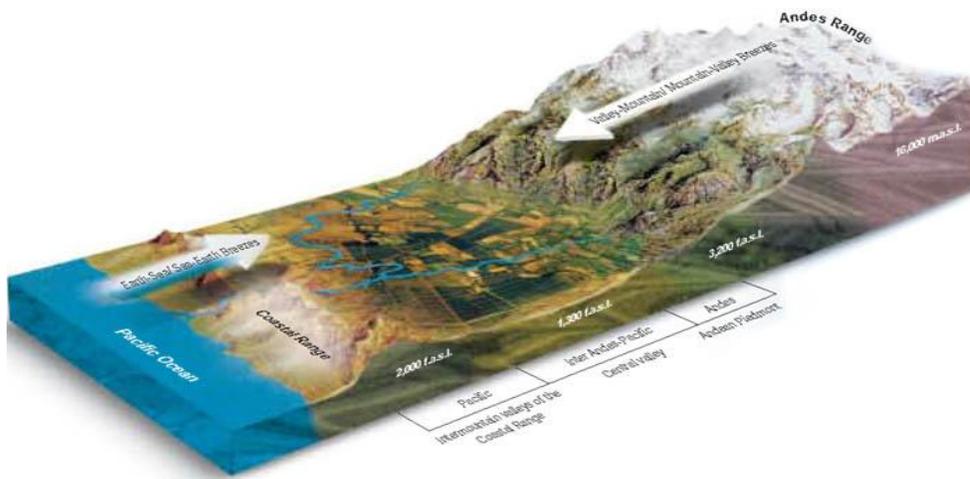


Figure 4: Geographical Section of the Central region of Chile.
Source: Wines of Chile⁶

In terms of soils, the central region of Chile contains a mixture of some excellent agricultural lands, many of which were originally covered with old-growth forests. The pre-Andean highlands, and some of the taller and more massive mountains in the coastal range, still contain large areas of old-growth forests of remarkable beauty. Most of this endemic forest area has been demarcated as national parks.

Santiago is the capital of Chile, and has the largest population in the country. The average monthly temperatures are about 19.5 °C /67.1 °F in the summer months of January and

⁶ " The Influence of the Pacific Currents on Chile's Climate," last modified August 12, 2013, <http://www.winesofchile.org/chilean-wine/viticultural-paradise/what-makes-the-difference/>

February, and 7.5 °C /45.5 °F in the winter months of June and July; the average monthly precipitation is no more than a trace in January and February and 69.7 mm (3 in) in June and July. In Concepción, by contrast, the average monthly temperatures are somewhat lower in the summer at 17.6 °C / 63.7 °F but higher in the winter at 9.3 °C / 48.7 °F, and the amount of rain is much greater: in the summer, Concepción receives an average of 0.8 inch (20 millimeters) of rain per month; in June and July, the city is pounded by an average of 10 inches (253 mm.) per month.⁷

3. Chilean Coastal Geography

The coastal geography is characterized mainly by the presence of the Coastal Range (*Cordillera de la Costa*). This mountain range runs from north to south along the Pacific coast of South America parallel to the Andean Mountains. It extends from Morro de Arica in the north, to Taitao Peninsula at the Chile Triple Junction in the south. The Coastal range has a strong influence on the climate of Chile because it produces a rain shadow to the east. Due to this, the vegetation growing on the seaward slopes is much more exuberant than in the interior. Compared to the coastal lowlands and the Intermediate Depression (flat area between coastal range and Andes mountains) it is sparsely populated with land use varying from protected areas to grazing and silviculture.⁸

⁷ "Geography of Chile," last modified January 5, 2014,
http://www.absoluteastronomy.com/topics/Geography_of_Chile

⁸ "*Sintesis Geografica Nacional*," last modified September 20, 2013,
http://www.ine.cl/canales/menu/publicaciones/compendio_estadistico/pdf/2012/2_sint_nacional.pdf.



Figure 5: Coastal landscape in the Central region of Chile.
Source: *La Vaguada*⁹

Along the more than 6,000 km of coastline, the Chilean coastal geography is very diverse, and the human settlement is mainly relegated to the mouth of rivers. Due to the sedimentation accumulating in the mouth of rivers, larger extensions of flat lands are found. For this reason, most of the coastal cities are associated with a river mouth. This also has other logical reasoning, which is the access to fresh water, which provides good land for agriculture.

The flat area, where the cities appear in the coastal region, is often called the coastal plain. In this area, there is a very diverse geographical composition, including rocks, cliffs, dunes, beaches, estuaries, and wetlands. In the coastal plain, the more protected locations, predominantly located near the southwest swell, are used for harbor activities. The consolidation of these city-harbors activates the local economy, leading to the creation of commercial routes, and promotion of commerce in the region.

⁹ "*Lenguados con mosca*," last modified August 20, 2008, <http://www.lavaguada.cl/reportajes/lenguado/lenguado.htm>

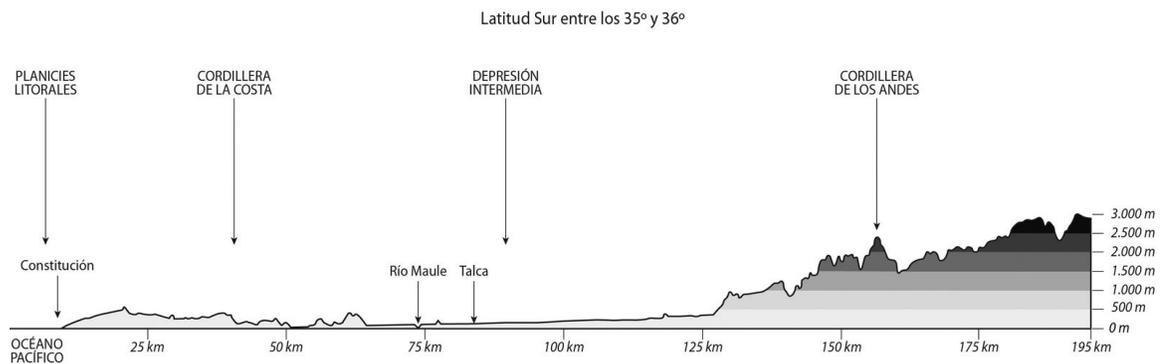


Figure 6: Topographic profile of Central Chile
 Source: MINEDUC ¹⁰

Most of the coastal towns, despite their size and population, describe an arrangement of the civic, residential, and industrial areas, and are separated into two main geographic conditions: the urban plain and the hills. Based on beneficial conditions for human habitation, the first area passes from the traditional native indigenous utilization into coastal towns. The presence of fresh water, good land for agriculture, abundance of fish and marine resources, and the Mediterranean weather, allow for a large concentration of people in these coastal towns. Once the lands in the plain were fully occupied, the hills started to be used for residential purposes. Later, the hills became the zone with the highest density.

¹⁰ "Perfil Topográfico Interpretativo Zona Central," last modified January 10, 2012, http://www.curriculumlineamineduc.cl/605/articles-19514_recurso_jpg.jpg



Figure 7: Valparaiso Harbor: Urban plain and hills.
Source: ASSERINT-COMEX CHILE ¹¹

Due to the intensive earthquake activity, including several tsunamis affecting Chile's central zone, the utilization as well as the restrictions for building in the plain area has changed considerably in recent centuries. In Chile, the flood maps have been historically developed from the most destructive event affecting certain areas. For this reason, the coastal plain is prone to experience radical changes in the role of the land due to the occurrence of earthquakes and tsunami activity. After the 2010 tsunami, most of the flood maps for the coastal towns in the central region of Chile were changed or updated, reflecting the information obtained from the flood generated by the tsunami waves.

As a consequence of the change in zoning, a large area at the coastline (flooded area) was modified in order to restrict its utilization as a residential area. New uses and building typologies were allowed in the flooded zones, such as touristic infrastructure as well as

¹¹ "ASSERINT-COMEX CHILE," last modified September 10, 2013, <http://asserint.cl/V1/>

green areas used as natural mitigation systems. These new green dissipation areas appear as an important protected area suggested by specialists, using local geography and natural resources to help in the rehabilitation of coastal towns affected by the 2010 tsunami.

B. Natural Disasters in Chile.

The entire planet experiences earthquake activity with different intensity. However, there are places where this kind of activity occurs with more frequency and intensity. The zone that registers the greatest amount of earthquakes is the Pacific's Ring of Fire.¹² In the Pacific's Ring of Fire, a large number of earthquakes are generated by the displacement of tectonic plates under the continental crust. An area about 40,000 km long (25,000 miles) experiences about 90% of the world's earthquakes and 81% of the world's largest earthquakes.¹³ Within this extensive area, there are zones where earthquake activity occurs more frequently and with more intensity; this includes Japan and Chile as the countries that register the greatest amount of destructive earthquakes in the recent history.

¹² Pilar Cereceda, Ana Maria Errazuriz, and Marcelo Lagos, *Terremotos y Tsunamis en Chile*, (Santiago: Origo, 2011), 5-6.

¹³ "Earthquake Topics for Education," last modified September 03, 2013, <http://earthquake.usgs.gov/learn/topics/>

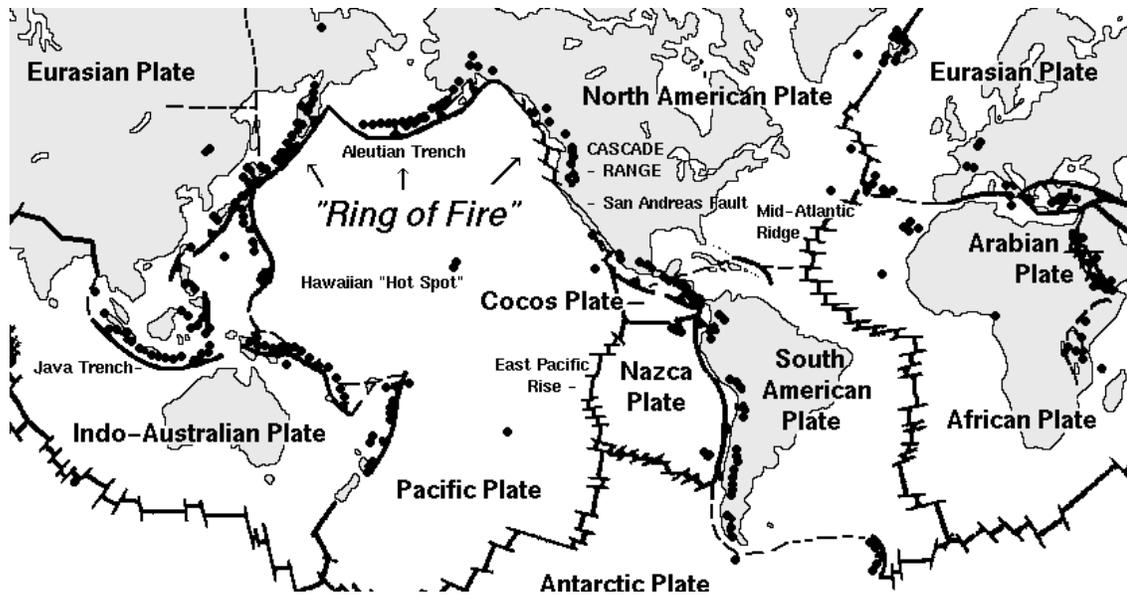


Figure 8: Active Volcanoes, Plate Tectonics, and the Ring of Fire.
 Source: COAL MINING AND GEOLOGY ¹⁴

Chile is a country located above the South American Plate, facing the Nazca Plate. These plates register intensive activity throughout recorded history. The national territory of Chile, from the frontier with Peru, until the southern location in the Hornos Cape, has experienced sixty-one earthquakes over magnitude 7.0 Mw registered from 1570 until 2010.¹⁵

Due to the nature of this phenomenon, an earthquake generated in certain zones of the Ring of Fire, can generate a tsunami wave able to travel across the Pacific Ocean. This affects a wide range of distant localities in addition to the localities placed close to the epicenter. In 1960, as well as in 2010, earthquakes with their epicenter along the Chilean coast generated destructive tsunami waves in several coastal localities around the Pacific's Ring of Fire.

¹⁴ " Tectonic Plates World," last modified January 2014,
<http://coalminingandgeology.com/geology/tectonic-plates-world/>

¹⁵ Pilar Cereceda, Ana Maria Errazuriz, and Marcelo Lagos, *Terremotos y Tsunamis en Chile*, (Santiago: Origo, 2011), 5-6.

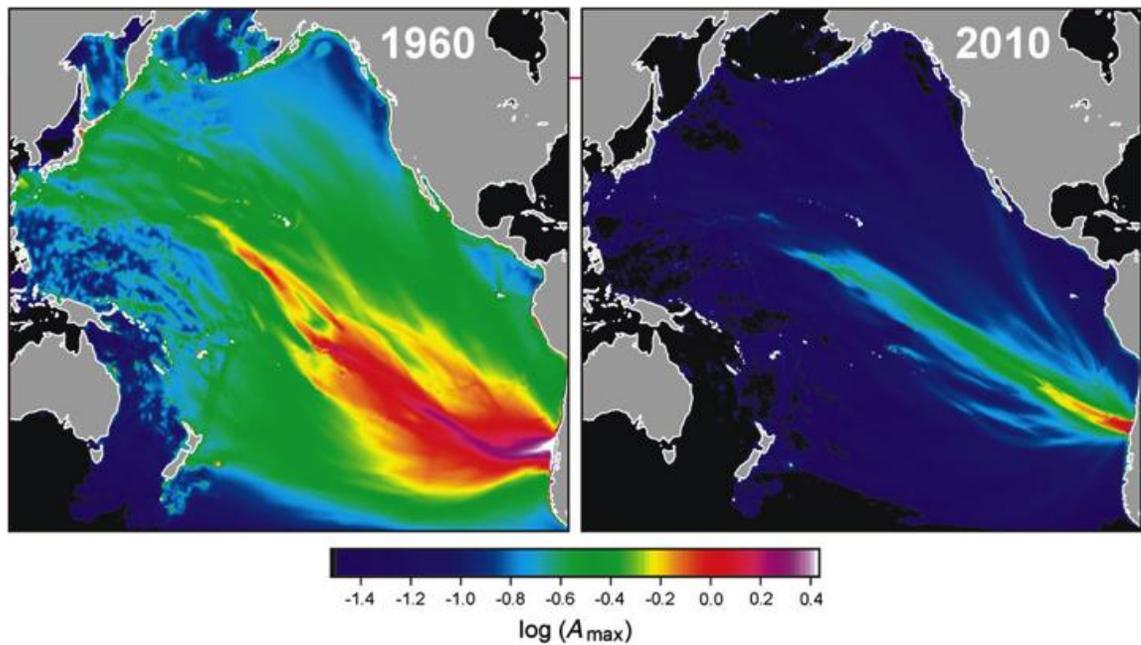


Figure 9: Tsunami Valdivia 1960 vs Concepción 2010, Chile.
 Source: Ocean Network Canada ¹⁶

There are numerous testimonies of strong earthquakes in the Chilean territory, since the days of the colonizers, especially in the central region of Spanish colonization. From the narrations from European colonizers and travelers, we can verify the destruction generated by this natural phenomenon, even in times when the cities had less construction and population. Since 1935, with the development of the Richter scale and the development of photography, it has been possible to track earthquake information and measurements. The earthquake in Valdivia, in 1960, was the first strong earthquake registered with modern technology. It has a magnitude 9.5 MW and is the strongest earthquake registered in the modern era.

As a result of this frequent destruction, the cities affected by earthquakes in the Chilean territory have experienced a constant renovation of urban infrastructure. People have had to adapt the building codes to fit the requirements of new and stronger earthquakes and tsunamis. The Chilean building codes were developed based on the codes of Japan, and

¹⁶ " Tale of Two Tsunamis," last modified Sept 5, 2012, <http://www.oceannetworks.ca/tale-two-tsunamis>

California State codes, due to the similarities in the soil quality and geography. After the 2010 earthquake, a new set of requirements for new buildings as well as new requirements and additions for existing buildings were added to the Chilean building codes.

Even though earthquakes and tsunamis have been the most influential natural disasters affecting Chilean territory, they are not the only threats affecting the population. Due to the change of currents affecting the Chilean coasts (Nino and Nina), some seasons, some specific areas, especially north and center, experience droughts. The winter season usually experience strong rain and wave storms along the entire Chilean coastline.

With less frequency, volcanic eruptions occur in Chile. The last strong volcanic eruption was in 2011, affecting Pulehue-Cordon Caulle, Chaiten. As a result of the eruption, at least 3,500 people were evacuated from nearby areas.¹⁷ This volcanic complex, located in the Andes Mountain Chain, produced activity, which expelled ashes and other materials, creating a five thousand meters ash cloud. Expert volcanologists calculated the energy liberated by the eruption equivalent to 70 nuclear bombs.¹⁸

¹⁷ "Chile volcano chain: Puyehue erupts, forcing evacuation," last modified June 05, 2011, <http://web.archive.org/web/20110607052029/http://www.bbc.co.uk/news/world-latin-america-13657187>.

¹⁸ "Chile's Puyehue Volcano eruption equals 70 atomic bombs," last modified July 13, 2011, <http://www.buenosairesherald.com/article/72965/chile-s-puyehue-volcano-eruption-equals-70-atomic-bombs>.



Figure 10: Major Volcanoes in Chile
 Source: GEOLOGY¹⁹

Between 1980 and 2010, the Chilean continental territory registered 61 events associated to natural disasters. These natural disasters generated 1581 deaths, resulting in a mortality rate of 51 people per year.²⁰ The second most destructive events affecting Chilean territory are rainstorms and floods. These storms take place especially in the center-south region of Chile, affecting agriculture and livestock. Even though several storms and floods take place every year in Chile, the immediate physical effect over people is small compared to the considerable effect on agricultural production.

¹⁹ "Chaiten Volcano," last modified January 2014, <http://geology.com/volcanoes/chaiten/>

²⁰ "Chile - Disaster Statistics," last modified September 18, 2013, <http://www.preventionweb.net/english/countries/statistics/?cid=35>.

Chapter II: Earthquake and Tsunami, Chile 2010.

A. Earthquake February 27th, 2010, Chile [27F].

During the morning of February 27th, 2010, a magnitude 8.8Mw earthquake affected the central region of Chile. The rupture zone was located about 35 Km out to sea from the coast of the Maule region (35.909S, 73.733W). The epicenter was located just 105 Km toward the north of Concepcion, one of the most populated cities in central Chile. This earthquake occurred near the rupture zone of the 1960's Valdivia earthquake, which was the largest earthquake registered in the modern history, at magnitude 9.5Mw.²¹



Figure 11: Earthquake Chile 2010 Epicenter and affected area.

Source: The New York Times²²

²¹ Pilar Cereceda, Ana Maria Errazuriz, and Marcelo Lagos, *Terremotos y Tsunamis en Chile*, (Santiago: Origo, 2011), 58-61.

²² "Maps of the Chile Earthquake," last modified March 3, 2010, http://www.nytimes.com/interactive/2010/02/27/world/americas/0227-chile-quake-map.html?_r=1&

The 27F earthquake could be felt in most of the Chilean territory, affecting approximately 80 percent of Chile's population. To date, it was the fifth largest earthquake ever recorded. Significant and numerous aftershocks occurred in the days and months following. Due to the high magnitude of the earthquake, considerable damage was registered in the infrastructure of the cities of the central region. Specific damage produced by the earthquake was observed in ports, buildings, roads, and bridges.

According to Chilean government officials, the number of deaths produced by the earthquake and tsunami was 525 people. The number of missing people was 25, and there were a total of about 12,000 people injured during the earthquake and tsunami.²³ Damage, resulting from the earthquake and tsunami, was caused to more than 800,000 people who were displaced from at least 370,000 houses, 4,013 schools, 79 hospitals, and 4,200 boats, from Valparaiso to Temuco.

At least 1.8 million people were affected in the more inhabited regions of the country: Araucania, Bio-Bio, Maule, O'Higgins, Region Metropolitana and Valparaiso. The total economic loss in Chile was estimated at 30 billion US dollars.²⁴ Electricity, telecommunication systems, and water supplies were disrupted, and the airports at Concepcion and Santiago resulted in minor damage.²⁵ The earthquake generated a tsunami which destroyed several coastal towns along the central region of Chile, also affected was Juan Fernandez Island located 670 Km off the coast of central Chile. Additionally the earthquake and tsunami generated some minor damage in coastal towns in California, and Japan.

²³ "Informe final de fallecidos y desaparecidos por comuna," Gobierno de Chile, last modified January 31, 2011, http://www.interior.gob.cl/filesapp/listado_fallecidos_desaparecidos_27Feb.pdf.

²⁴ "Chile puts quake damage at \$30bn," BBC News, last modified March 12, 2010, <http://news.bbc.co.uk/2/hi/8565493.stm>.

²⁵ "Magnitude 8.8 - OFFSHORE BIO-BIO, CHILE," USGS, last modified May 08, 2013, <http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/>

B. Tsunami February 27th, 2010, Chile.

As a result of the February 27, 2010 earthquake, tsunami waves were generated. These waves hit the coastal towns with great intensity in the central region of Chile, from Valparaiso to Tirua. The tsunami also affected the Juan Fernandez Islands, located 600 Km offshore. Several towns in many countries around the Pacific Ring of Fire reported increased tides and swells. The tsunami alert was extended to 54 countries and territories around the Pacific Ocean.²⁶ Even though the earthquake was 8.8 on the Richter scale, the depth was 35 Km, which may have limited the tsunami's magnitude.

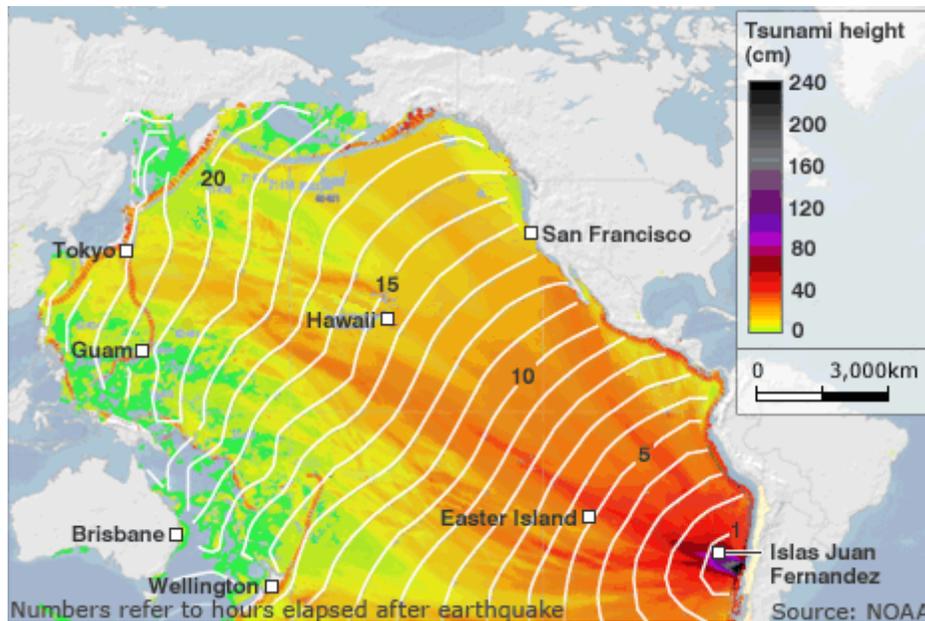


Figure 12: Tsunami height along the Pacific Ocean.
Source: BBC²⁷

Analysis of the impact of the waves in the affected coastal towns shows that the shape of the offshore and near shore bathymetry (ocean's depth map) has a high relevancy in the

²⁶ "TSUNAMI BULLETIN NUMBER 005," PACIFIC TSUNAMI WARNING CENTER, last modified February 27, 2010, <http://web.archive.org/web/20100301011944/http://www.prh.noaa.gov/ptwc/messages/pacific/2010/pacific.2010.02.27.104329.txt>.

²⁷ " Map: Chile quake tsunami," BBC News, last modified February 28, 2010, <http://news.bbc.co.uk/2/hi/8541833.stm>

tsunami wave height and therefore in the damage registered to buildings and urban infrastructure. Topography is an important component used to define water behavior in coastal towns. Due to the great geographical diversity in the central Chile coastal towns, extreme variability in the height of tsunami waves impacted the affected coastline. Many towns near to the epicenter were not affected by tsunami flood due to their diverse geography.

The first tsunami waves arrived less than 30 minutes after the earthquake. The affected coastal towns reported between two and four tsunami waves. For example, in the harbor city of Talcahuano, the approximate arrival time for the first wave was at 3:54AM, the second wave at 5:30AM, the third wave was reported at 6:00 AM, and the fourth wave at 6:40 AM.²⁸ In most of Chilean coastal towns the geography allows people to move from the coast to near hills (safe zone) in a short time. People tend to evacuate coastal areas after big earthquakes right after the earthquake finishes, with no necessity of an evacuation alarm. Experience and tradition precipitate the need for an alarm.

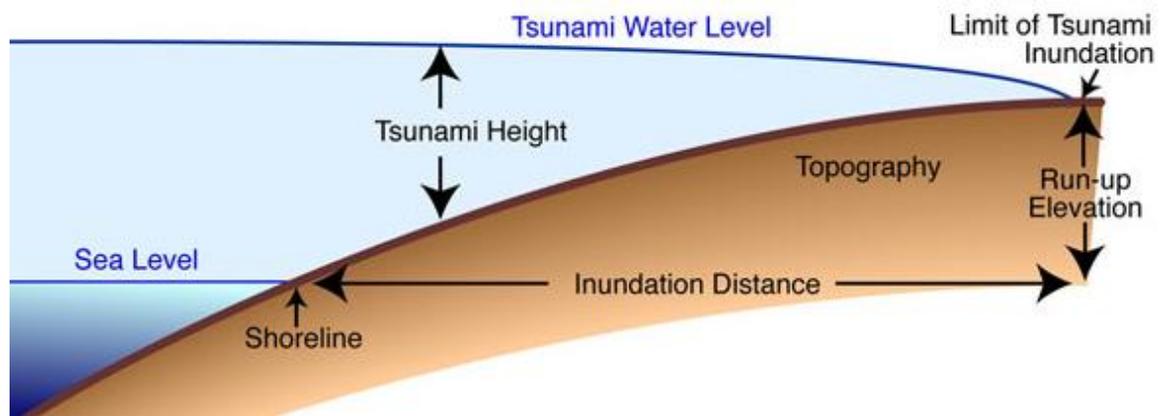


Figure 13: Tsunami Inundation Diagram
Source: Discover Tsunamis²⁹

²⁸ Billy L. Edge, *Chile Earthquake and Tsunami of 2010* (Reston, Virginia: American Society of Civil Engineers, 2013), 14.

²⁹ "Tsunami terms diagram," last modified January 2014, <http://www.discovertsunamis.org/images/tsu-terms-diagram.jpg>

The tsunami occurred during the falling tide, which helped in the reduction of the tsunami height as well as the inundation distance from the shoreline. The tsunami height level registered by the different survey teams was between 10 and 12 meters (30-60ft). Several run-ups were registered along the affected zone. The most significant run-up wave height of 30 meters (90ft), and was located next to the town of Tirua.³⁰

The majority of the damage, registered by the action of the tsunami, was from structural failure due to hydrodynamic loading, the impact of debris and buoyant elements, the impact from large boats, and scouring at foundations. Most of the timber structures, located in coastal areas, resisted the earthquake shake, due to the flexible properties of wood. However, they were destroyed due to the effect of the tsunami. Reinforced concrete buildings performed very well structurally, even when flooded higher than the ground floor level. There were towns where significant scouring destroyed concrete and masonry buildings due to sandy soils. Another significant impact from the tsunami was the vertical lift forces from the water on submerged objects such as piers and bridges.

The main economic activities that sustain life in the affected coastal areas are fishing, tourism, and various forms of local commerce. These three activities were seriously affected due to the destruction of the earthquake and tsunami. In addition, the human and animal losses added to the loss of work sources, as well as access to natural resources. The tsunami also generated significant water pollution, affecting the delicate marine ecosystem. At the same time, the drainage infrastructure collapsed, creating source points of polluted water, having a detrimental effect on agriculture. The change in soil salinity from tsunami flooding, adversely affected the coastal landscape.

³⁰ Billy L. Edge, *Chile Earthquake and Tsunami of 2010* (Reston, Virginia: American Society of Civil Engineers, 2013), 17.



Figure 14: Wood debris in Mariscadero.
Source: Felipe Iguait 2010

The mouth of the rivers also became highly flooded and eroded due to the low resistance to tsunami waves. In some towns, construction next to the river was totally destroyed, even in buildings located far from the shoreline.

The tsunami inundation in coastal cities and small towns resulted in hydrodynamic loading on structural elements of buildings and urban infrastructure. Most of the scour occurred during drawdown as the inundating water receded, dragging all class of debris. Timber framed houses as well as unreinforced or poorly reinforced masonry structures, sustained severe or total damage due to the hydrodynamic loads.³¹

Reinforced concrete buildings performed very well, even when inundation reached above the second floor level. In this typology of building, the non-structural components of the

³¹ Ian Robertson, Gary Chock, and Juan Morla, "Structural Analysis of selected Failures caused by the 27 February 2010 Chile Tsunami," *Earthquake Spectra* Vol. 28, no. 1 (2012): 215-243.

buildings, such as windows, doors, and lightweight partitions were totally destroyed. The destruction of these lightweight elements performed positively in the structures, helping them to reduce lateral load due to the flow of the caudal inundation. In harbor-cities, such as Talcahuano, the buildings and coastal infrastructure was mainly affected by debris impact, especially fishing boats and shipping containers.

Chapter III: Pelluhue County Analysis

A. Pelluhue County Overview.

1. Geographic Context

Pelluhue County is located in the southwest zone of the VII region, the central zone of Chile. Pelluhue County is part of Cauquenes province local government. Its coastline faces the Pacific Ocean. The geography of the territory is defined by a transversal (east-west) topography. The towns are mostly located in the coastal plains, surrounded by beaches, dunes, and coastal mountains. Next to the coastal plain is the Coastal Range, which contains the highest hills in the coast area.

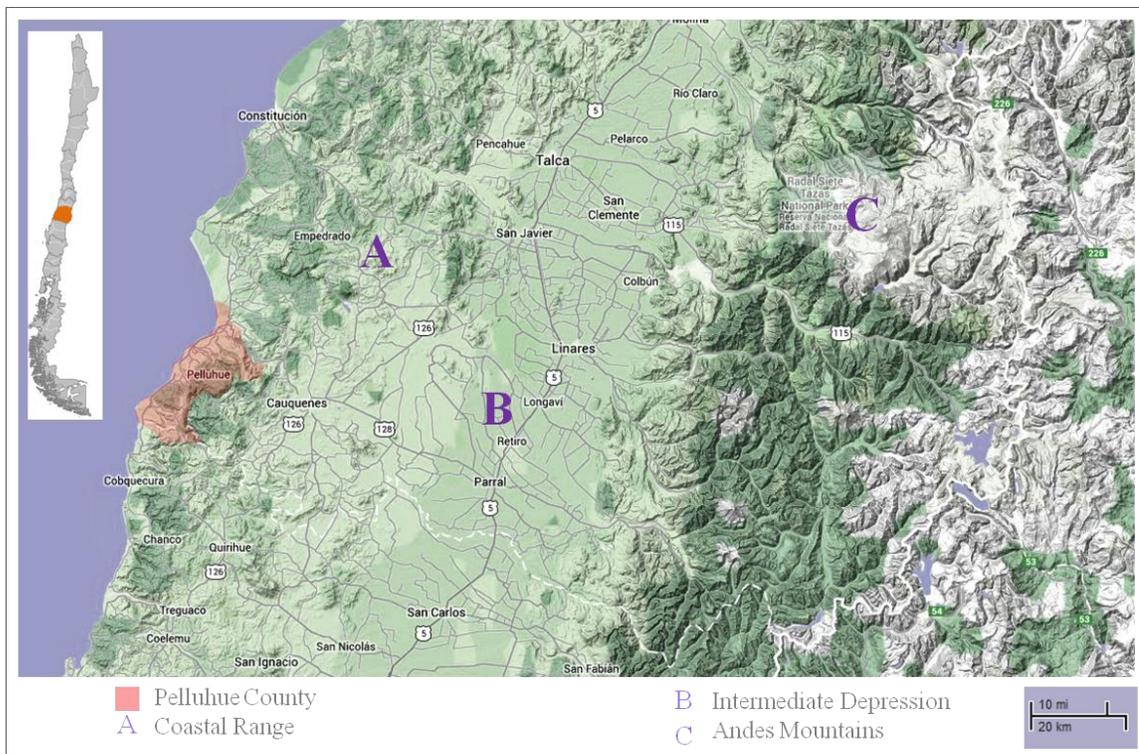


Figure 15: Pelluhue County in the VII region of Chile.
Source: Felipe Igualt + Google.cl/Maps.

Pelluhue County has an area of 372 sq km (145 sq mi). It is comprised of Pelluhue, Mariscadero, and Curanipe, as the main urbanized villages. The coast maintains most of the population. The towns of Pelluhue and Curanipe concentrate most of the population, because of the availability of basic services and good road connectivity. Pelluhue town has a surface of 1 sq km (0.38 sq mi). Curanipe has 0.4 sq km (0.15 sq mi), which is less than half of the area of Pelluhue town. Due to the expansion of Pelluhue town toward the north, the locality of Mariscadero has been consolidated, being the third biggest locality in Pelluhue County.³²



Figure 16: Pelluhue County coastal towns.
Source: Google Earth 2013.

The population registered in Pelluhue county in the 2002 census was 6,414 people. The population projected for 2012 was 7,990 people.³³ This population can increase to 35,000 people in the summer, due to influx of people vacationing in coastal areas. The territory has a greater population density toward the seaside and decreases toward the hill side.

³² Ilustre Municipalidad de Pelluhue, *Plan Regulador Comunal de Pelluhue: Memoria Explicativa* (Santiago: Habiterra, 2012), 3-13.

³³ "Reportaje estadístico comunal Pelluhue," last modified March 1, 2013, <http://reportescomunales.bcn.cl/2012/index.php/Pelluhue>

Historically the population was placed in the coast due to the association with coastal activities, such as fishing, seafood production, and maritime transport. Maritime transport is the most important activity in Pelluhue County throughout the twentieth century. The geographic conditions allowed for the development of a strong forestry industry in the region. These activities were the cause of the high demand of maritime transportation in the first half of twentieth century. In the second half of the century, together with the development of road system, the coastal localities were best connected with the interior of the country. This improved the supply of coastal towns, but also changed the historic relationship of population of the coastal areas.

Pelluhue County has temperate weather with Mediterranean characteristics. Due to the influence of the sea, there is high atmospheric humidity in the coastal zone.³⁴

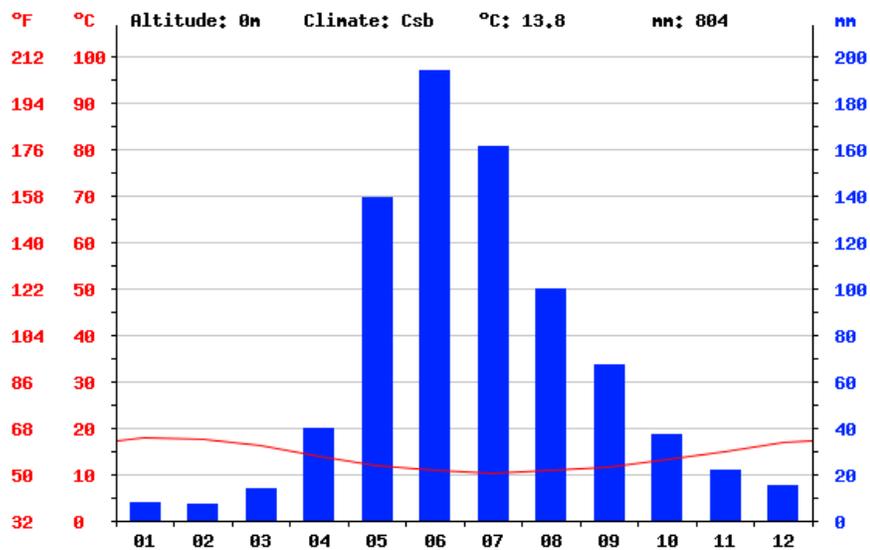


Figure 17: Weather Chart for Pelluhue County.
Source: Climate-Data³⁵

³⁴ "Descripcion Climatologica, Region del Maule," last modified October 30, 2013, http://www.meteochile.cl/climas/climas_septima_region.html

³⁵ "Clima: Pelluhue," last modified October 30, 2013, <http://es.climate-data.org/location/21708/>

2. Historical Description of Pelluhue County

The name Pelluhue comes from the local Mapudungun language, and means ‘land of clams’, due to the abundance of clams on the beach. Curanipe in local Mapudungun language means ‘black stone’. The Picunches Indians originally occupied the area where Pelluhue County is located.³⁶ Mariscadero in Spanish means ‘the place where you collect seafood’.

Since the beginning of the twentieth century, together with the expansion of the Chilean economy, as well as the growth of cities in the central Valleys, the coastal towns started to consolidate as resorts. In 1935 the main attractions were the sea baths and the beautiful landscape. In 1951 the local authorities decided to improve the county's connectivity, building new roads to connect with the big cities, and the improvement of old roads.³⁷



Figure 18: Oxcart in Pelluhue, 1951.
Source: Curanipe 1850³⁸

³⁶ "Historia Chilena, Mapa de los pueblos originarios," last modified May 29, 2007, <http://www.educarchile.cl/ech/pro/app/detalle?ID=132542>

³⁷ "Resena Historica de Pelluhue," last modified October 8, 2013, <http://www.munipelluhue.cl/history.htm>

³⁸ "Curanipe, Navegando en el tiempo," last modified October 8, 2013, http://curanipe1850.blogspot.com/2007_05_01_archive.html

Today, Pelluhue and Curanipe are both popular coastal resort areas. Pelluhue evolved from a modest fishermen's cove to a crowded summer resort within the last 50 years. The town's population swells to more than several thousand in the summer weekends when vacationers from the hinterland (Cauquenes, Linares, Parral, Talca) visit the seaside. Curanipe evolved from a small harbor and resort for the Cauquenes elite to a modest coastal fishing village.

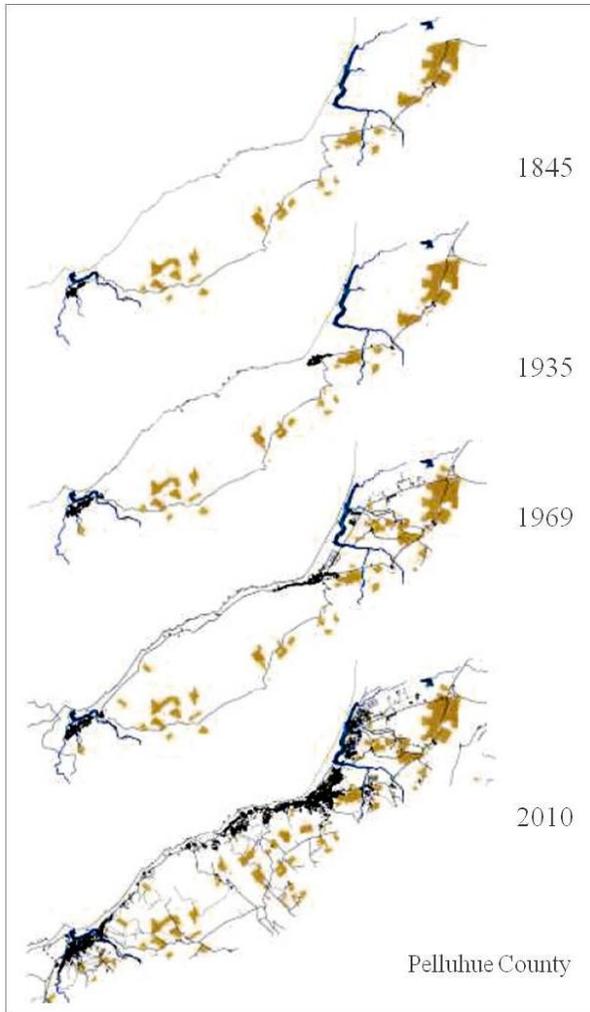


Figure 19: Urban evolution in Pelluhue county.
Source: *Ilustre Municipalidad de Pelluhue*³⁹

³⁹ Ilustre Municipalidad de Pelluhue, *Plan Regulator Comunal de Pelluhue: Memoria Explicativa* (Santiago: Habiterra, 2012).

3. Economics and Development

In Pelluhue County the economic activities are varied, however they have a limited scope as well as a limited potential for expansion. The agricultural production is not significant, needing external supply to satisfy the local demand for vegetables. This situation occurs because of the lack of good soils for agriculture in the coastal area. However, the soils are advantageous for forest production. The forest industry prefers to plant fast growing species instead of native forest species. Local endemic species improve the quality of soils, while non-native species, such as pines and eucalyptus, can affect the organic composition of soils. Because of the introduction of invasive, quickly growing species, the quality of soils has been seriously affected by the forest industry. Today, the most exploited items are forest crops and natural grasslands.



Figure 20: Native Forest v/s Pine forest.
Source: Felipe Igualt 2013

Another important commercial activity in Pelluhue County is fishing. This activity maintains the same characteristics as it did twenty years ago. The fishing activity is developed in the traditional artisanal way. The main fishing villages are placed in Curanipe, Pelluhue town, and Cardonal. Industrial activities are very unusual in this area, and are mostly related with the industry of bread production (industrial crops and mills).

With less frequency there are sporadic industrial activity from construction and woodworking.⁴⁰



Figure 21: Artisanal fishing activities in Curanipe.
Source: Adrenaline Chile⁴¹

The economic activity that offers the greatest potential for development of this zone is the local tourism industry. In the last decade the demand of tourism amenities increased considerably. This situation is realized in the increase in the number of hotels and cabins in Curanipe and Pelluhue town. These buildings take advantages of the great natural landscape. Tourism works to activate the commercial activities, providing a large number of small stores to supply the demand of food and liquor. Even though the tourism supports the local economy, it also brings unwelcome urban conflicts such as the collapse of the coastal road, as well as the pedestrian pathways. Another important problem associated with tourism in the summer season is the collapse of the potable water supply, which is unable to sustain the necessary demand by the dramatic increase of the number of people in the county.

⁴⁰ Ilustre Municipalidad de Pelluhue, *Plan Regulador Comunal de Pelluhue: Memoria Explicativa* (Santiago: Habiterra, 2012), 40-43.

⁴¹ "Volcom Pelluhue," last modified August 2012, <http://adrenalin.cl/nutcracker/?p=156>

Outdoor sports have had a significant increase in popularity in the last years in Pelluhue County. The geographic conditions previously described, as well as the good conditions for practicing aquatic sports, have attracted hundreds of tourists to visit Pelluhue to practice sports. Every year there is a massive congregation of surfers taking advantage of the good surfing conditions. The contingent of tourists and sportspeople support the operation of small commerce in the region. The growth patterns of big cities near Pelluhue County show yearly increase, as do the demand for touristic services. This lends itself to the development of the tourism industry in the coastal area of Pelluhue County via touristic services.⁴²

B. Pelluhue County Infrastructure.

In Pelluhue County, most of the essential urban infrastructure was located in the zone affected by tsunami, including the main coastal road, which connects the towns in the county, and is the only connection road with the other counties in the region.⁴³ Most of the urban infrastructure was placed without considering potential risks of destruction due to natural forces. The earthquake and tsunami exposed the fragility of the urban infrastructure in towns lying within the central region of Chile, especially in coastal towns. Before the tragedy most of these towns didn't have a map of risks to define zones prone to natural disasters.

⁴² "Curanipe Surf," last modified October 28, 2013, <http://www.surflockerchile.com/uncategorized/curanipe/>

⁴³ Ilustre Municipalidad de Pelluhue, *Plan Regulador Comunal de Pelluhue: Memoria Explicativa* (Santiago: Habiterra, 2012), 2-4.

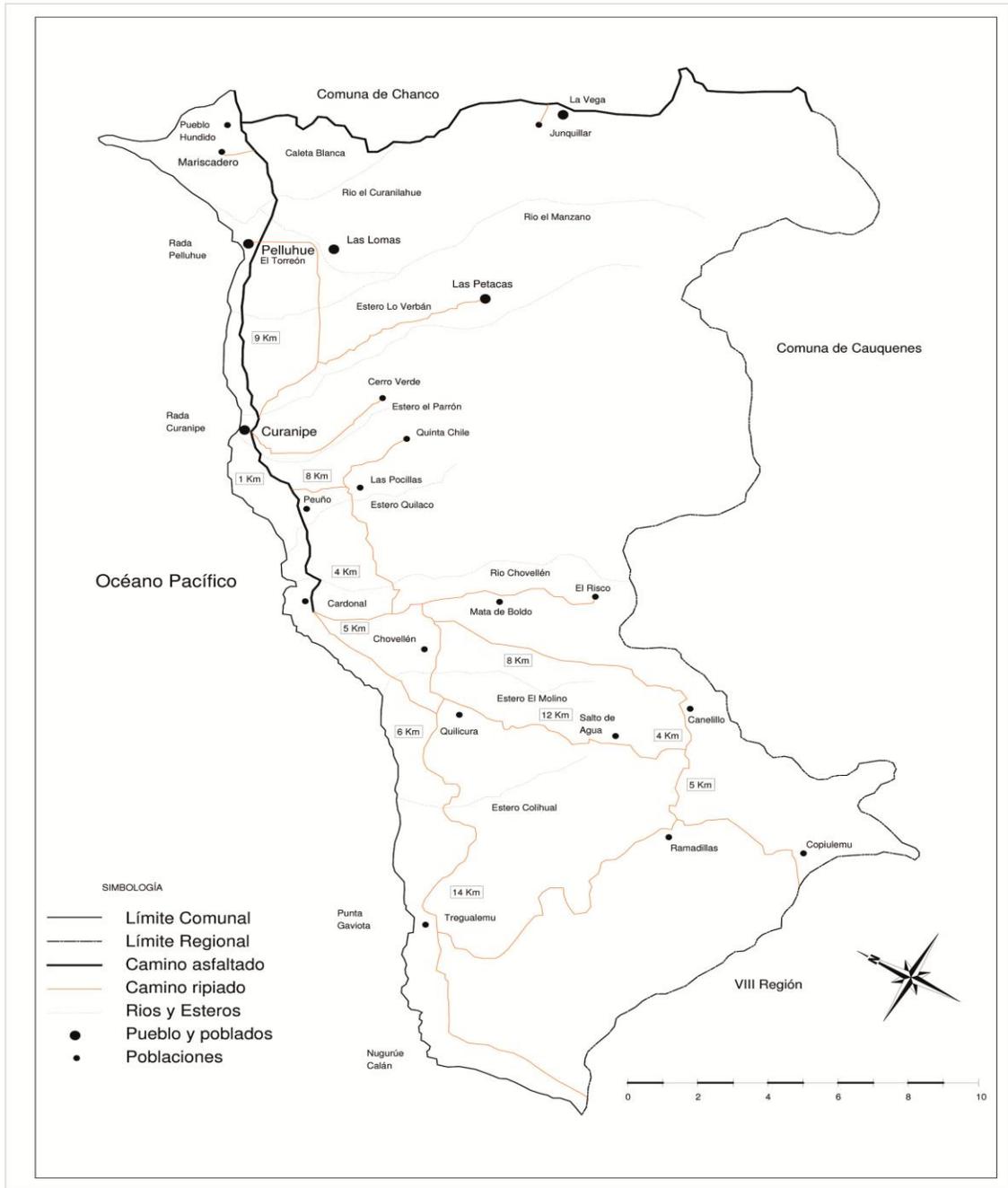


Figure 22: Pelluhue County general Map
 Source: *Ilustre Municipalidad de Pelluhue* ⁴⁴

⁴⁴ Ilustre Municipalidad de Pelluhue, *Plan Regulador Comunal de Pelluhue: Memoria Explicativa* (Santiago: Habiterra, 2012).

1. Road System

The Pelluhue County road system can be separated in two systems. The first is the main road web that connects the county with the other populated areas in the coastal region, as well as with the main cities where commercial supplies originate. The second is the secondary road system, which allows the residential population access to services and resources offered within the city limits.

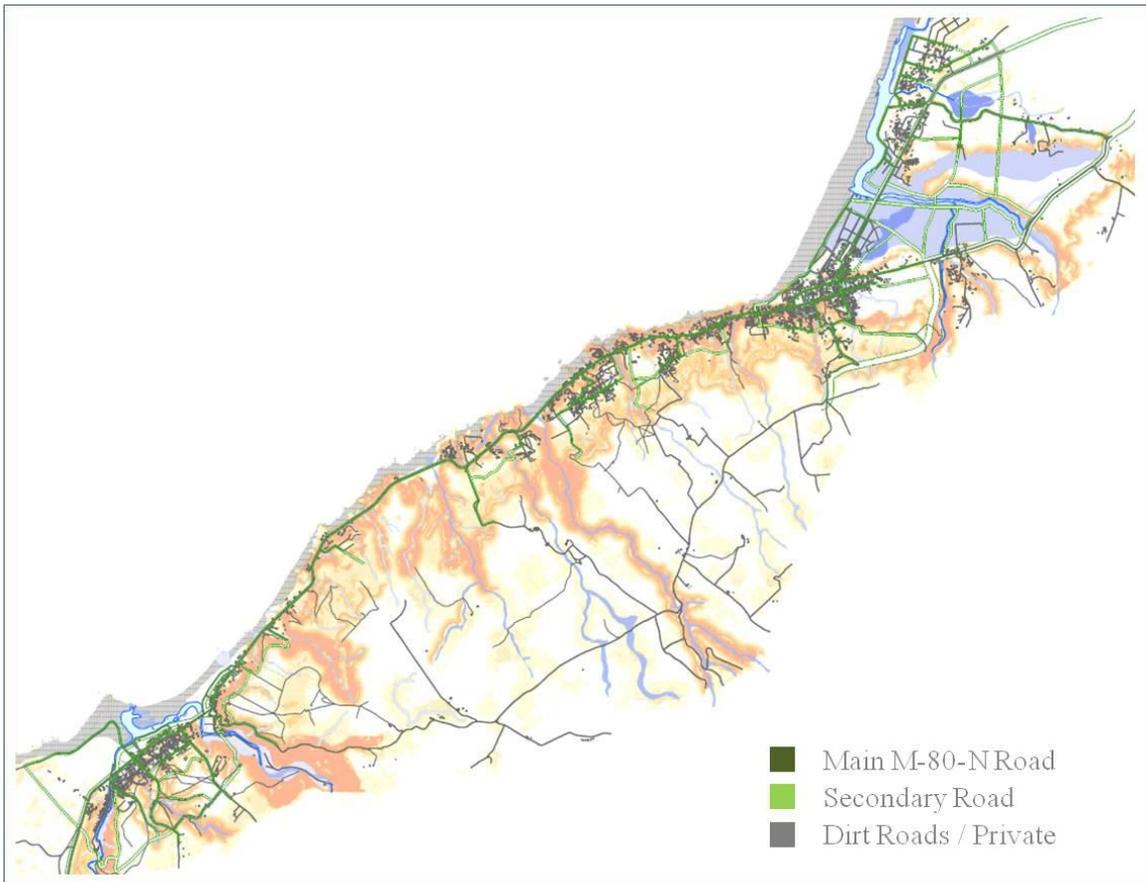


Figure 23: Pelluhue County Main Roads
Source: Felipe Iguait 2014

The Road M-80-N is the axis connecting the north and south sides of the county. As a part of the National Coastal Road, this road also provides the connection between Pelluhue County and the neighbor counties along the coastline. Concentrated along this

road are the main utilities and commercial area, as well as a majority of the population. The Road M-80-N goes through Pelluhue and Curanipe towns, bringing transit congestion and noise pollution in the towns during the summer season.⁴⁵



Figure 24: M-80-N Road along Pelluhue County
Source: Google Earth 2013.

The Road M-80-N is placed into the flood zone in several segments along the county. During the earthquake and tsunami 27F, there resulted serious damaged in the section between Mariscadero and Curanipe. Because of the complex geography where it is located, local authorities took a long time to resuscitate the function of the road. After the tsunami it was necessary build a new road system, which offers a greater coverage and is less susceptible to natural disasters.

⁴⁵ Ilustre Municipalidad de Pelluhue, *Plan Regulador Comunal de Pelluhue: Memoria Explicativa* (Santiago: Habiterra, 2012), 33-36.

2. Transportation Systems

The movement of people occurs mainly through the use of public transportation and by private vehicles. Along the M-80-N Road there is a set of public transportation stations. The main stations are placed in the public area of the center zone of Curanipe and Pelluhue town. Due to the weather conditions the stations relocate throughout the year. Most of the bus stations offer minimal weather protection. On a daily basis, the county's population travels long distances to access basic services of commerce, work, or education.

There exists a small airport placed next to south side of Curanipe town, which has been used for emergency medical assistance, but is seldom used during the year. Private customers mainly use the airport in support of the aerial route along the Chilean coast.

a. Harbors infrastructure

Pelluhue County doesn't have industrial harbor activity, and the harbor infrastructure is used for the local fishing business. This infrastructure was seriously affected by the tsunami in 2010, not only in the physical infrastructure, but also the availability of the main source of food of the population. There are three fishing villages in the county, placed in Pelluhue town, Curanipe town, and Cardonal to the south of Curanipe.



Figure 25: Curanipe and Pelluhue Fishing villages.
Curanipe: Felipe Igualt 2012

The main fishing village prior to 27F was Pelluhue. The earthquake raised the land, changing the conditions to operate in the fishing cove. Today, the fishing village of Pelluhue has been displaced to Curanipe, where both fishing coves operate in Curanipe beach. Due to the importance of the supply of fish and seafood to the population, it has been important for local government to rebuild the harbor infrastructure.



Figure 26: Pelluhue Fishing village before and after 2010 tsunami.
Source: Felipe Iguait 2012

3. Communications

The telecommunications network in Chile is similar to that in the United States, both in terms of hardware and architecture. There is a central system of energy storage called SIC, which distributes energy to the population via a distribution network. In addition to optical fiber cables connecting the SIC with remote switches, both copper cables and microwaves are used. Cellular phones have becoming the most popular telecommunication tool, not only for the public, but also for utilities using it as their service dispatch tool. Microwave is mainly used for reaching locations where cables are

extremely difficult and costly to install. Because of the frequency of natural disasters in Chile, this system is in a constant process of modernization.⁴⁶

The performance of the communication system in the earthquake-affected area was moderate to poor. The main failures and damages reported were: equipment failure, batteries fallen off racks, severed cables, backup power generator failure, and tower and antenna failures.⁴⁷ The damage to the distribution system was mainly from building failures that pulled the drop wire from the utility poles. The cellular network was one of the most affected, with more that the 40% of BTSs devices (tower and antenna) affected in the central zone of Chile.



Figure 27: Cellular BTSs devices in Curanipe.
Source: Felipe Igualt 2013.

⁴⁶ Alex K. Tang and John M. Eiding, *Chile Earthquake of 2010, Lifeline Performance* (Reston: American Society of Civil Engineers, 2013), 241.

⁴⁷ Alex K. Tang and John M. Eiding, *Chile Earthquake of 2010, Lifeline Performance* (Reston: American Society of Civil Engineers, 2013), 244.

Landline telephonic service recovered faster than wireless coverage. This is because most of the network outages were caused by the lack of power to distribute the telephonic network. Cellular service providers reported heavy damage in addition to the electric power outage. In the remote areas, access to restore damaged equipment or to provide power became extremely difficult due to damage to bridges and roads.⁴⁸

4. Electricity

In Pellahue County the electrical service is provided by the EMEL electric company, headquartered 50 kilometers to the east in Cauquenes. This company is the same that provides electric power to most of the region. There is no power plant in the area, and the electrical company takes the energy from the SIC (Interconnected Central System), which is along the M-89-N road.⁴⁹

The street lighting system covers most of the road system in the county, with the exception of the southern localities such as Tregualemu and Ramadilla, where the houses are connected to the electric supply network, but the streets do not provide public illumination.

The 27F earthquake damaged the electric infrastructure of the aboveground post and wire system. The county's community went a long time without electricity service. During the first month after 27F, most of the electric wire and posts were replaced. Even though today the system works regularly, the old posts and wires should be replaced by underground electric service, in order to reduce the visual pollution as well as reduce risk of collapse in future natural disasters affecting Pellahue county.

⁴⁸ Alex K. Tang and John M. Eidinger, *Chile Earthquake of 2010, Lifeline Performance* (Reston: American Society of Civil Engineers, 2013), 249.

⁴⁹ "CDEC-SIC," last modified October 29, 2013, http://www.cdec-sic.cl/contenido_en.php?categoria_id=1&contenido_id=000001



Figure 28: Electric infrastructure affected by 27F Tsunami.
Source: Felipe Igualt 2010.

Furthermore, alternative sources of energy could to be used in Pelluhue. Even though solar energy is limited due to the constant cloudiness, most of the tourist services have implemented solar panels to supply electricity. Wind is abundant in the coastal zones; however, this resource has not been utilized for energy generation.

5. Water / Sewage

The first water pipe was installed in 1951 in Pelluhue County. Previously the water was carried from a close river to the houses.⁵⁰ Today the sanitary infrastructure in Pelluhue County is comprised of the drinking water system and the sewer system. There are two main drinking water plants in the county, placed in Pelluhue town and Curanipe town. These two plants supply the majority of homes in the county. In places difficult to access, it is common to use the wells for drinking water.

⁵⁰ "Resena Historica de Pelluhue," last modified October 8, 2013, <http://www.munipelluhue.cl/history.htm>

The drinking water system is made up of two catchment points in Pelluhue and Mariscadero. The catchment points are placed in a high zone along the rivers where the water is cleaner. Then this water is directed toward aspiration and elevation plants to be distributed into the tanks that supply water to the people. The disinfection of the water is conducted by a simple process of chlorine gas injection due to the good quality of water captured in the rivers. Because the population is divided between the plains and hills, the distribution network is divided in a high network and a low network.

Due to the complex geography, the wastewater sewer system collects wastewater and directs it toward the treatment plant. The wastewater is separated in stabilization pools, for additional purification before being returned to the river. Even though the efforts to cover the full demand of the population, the wastewater sewer system covers a 53.2% of demand in Pelluhue, and a 74.4% in Curanipe.⁵¹ The rest of the demand has to be resolved by using septic tanks.

Due to the low population in the county, the government has not integrated a rainwater collection system. For this reason, the towns in Pelluhue County do not have an exclusive rainwater collection system. The rainwater flows to the rivers following the natural slope, and then flows toward the sea. The main consequence of not having a rainwater system is the destruction of roads due to the water erosion, as well as landslides and floods.

⁵¹ Ilustre Municipalidad de Pelluhue, *Plan Regulador Comunal de Pelluhue: Memoria Explicativa* (Santiago: Habiterra, 2012), 39.

Chapter IV: Tsunami Flood Analysis in Pelluhue County

The 8.8 Richter earthquake generated three tsunami waves that breached the coast of Pelluhue. The first wave arrived 30 minutes after the end of the earthquake. The second wave arrived one hour after the first, and the third one and a half hours after the second. The highest tsunami wave was the second, which constituted the majority of the destructive force.⁵² The 27F tsunami and earthquake caused severe damage in Pelluhue County and caused the death of 37 people. During the tsunami action, the tide was in its lowest condition, which significantly decreased the flood level. Also, during the February 27th night it was full moon, allowing people of the uptown villages to clearly see the arrival of the waves at 4:00 am.

A. Urban equipment after 27F

Immediately following the earthquake, the residents escaped to the higher areas in the hills. However, most of the tourists escaped toward the coast, where the tsunami flood directly affected them. The flood of the city generated erosion in floors and walls. The run-up (higher flood point) varied by geographical situations. In Curanipe, the run-up was located in the center of the town, reaching 6.55 meters. In the area of San Pedro Rock was measured a maximum run-up of 6.3 meters.

In the north area of Pelluhue County, damages were concentrated and identified along the north coastal edge in Mariscadero town where almost 70 % of the properties were destroyed. The fishing village was damaged, and the fire station and two educational establishments were flooded and sustained structural damage. There was widespread destruction along the low-lying area of Pelluhue town, mainly because of the tsunami inundation. Several tsunami run-ups took place in the north area of Pelluhue, especially in Mariscadero town. In this area a maximum run-up of 14.5m was measured (47 ft).

⁵² Billy L. Edge, *Chile Earthquake and Tsunami of 2010* (Reston: American Society of Civil Engineers, 2013), 13-15.

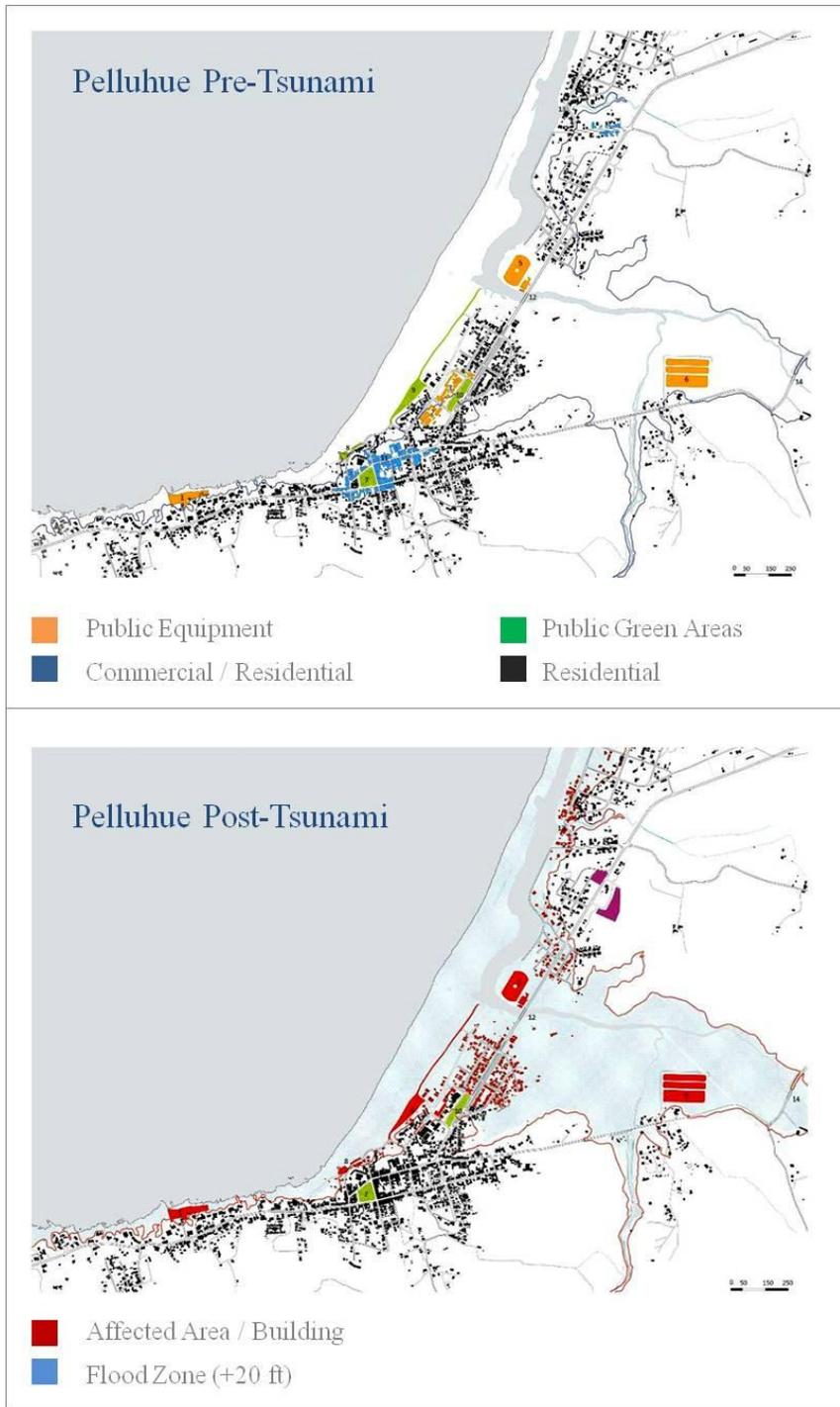


Figure 29: Pre and post-tsunami Pelluhue 2010
 Source: ACUA 2011⁵³

⁵³ "Estudio de Prefactibilidad Mejoramiento Borde Costero Curanipe Pelluhue, comuna Pelluhue, Región del Maule," ACUA, last modified May 5, 2011, http://dc254.4shared.com/doc/pGgi4aa_/preview.html

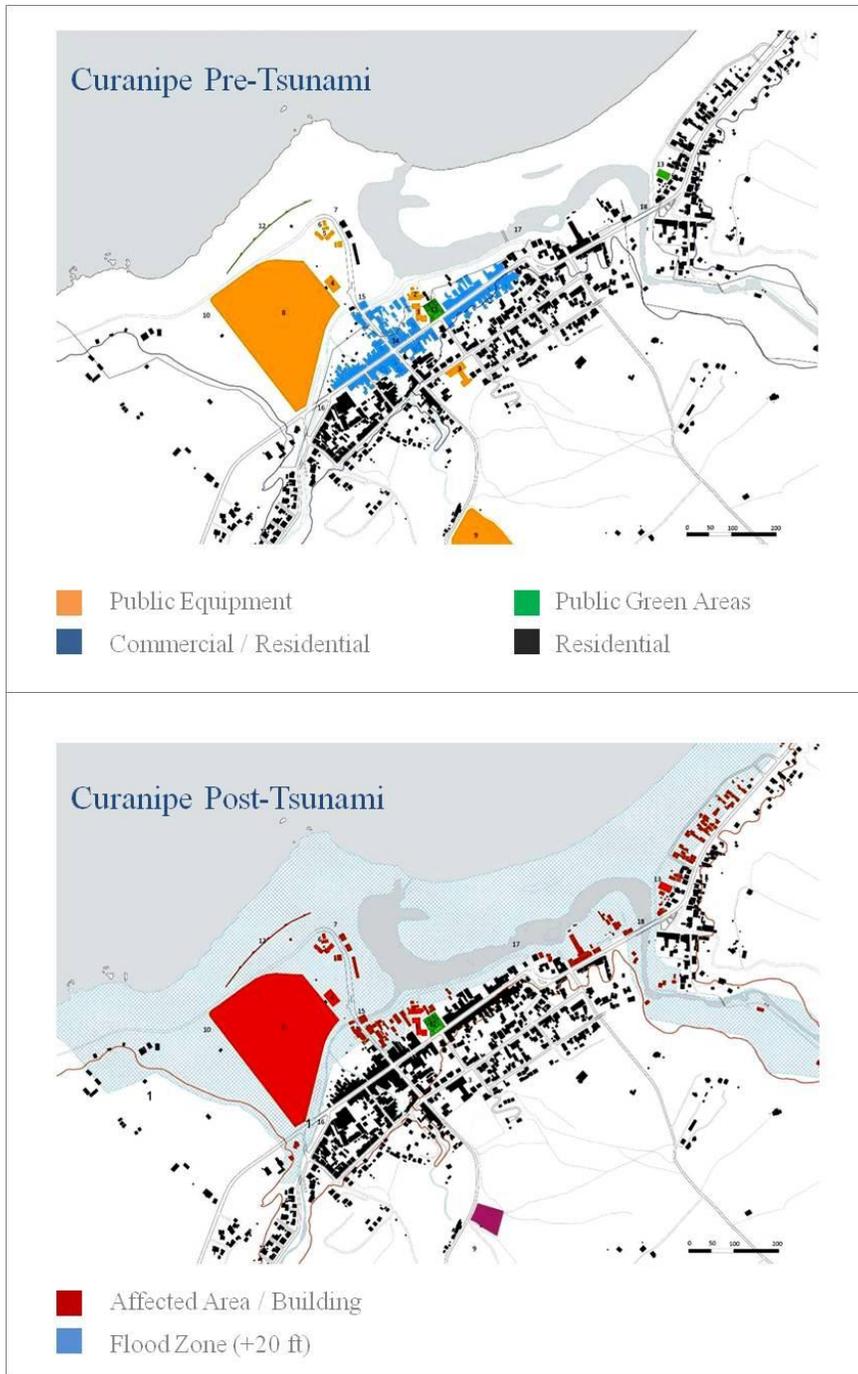


Figure 30: Pre and post-tsunami Curanipe 2010
 Source: ACUA 2011⁵⁴

⁵⁴ "Estudio de Prefactibilidad Mejoramiento Borde Costero Curanipe Pelluhue, comuna Pelluhue, Región del Maule," ACUA, last modified May 5, 2011, http://dc254.4shared.com/doc/pGgi4aa_/preview.html

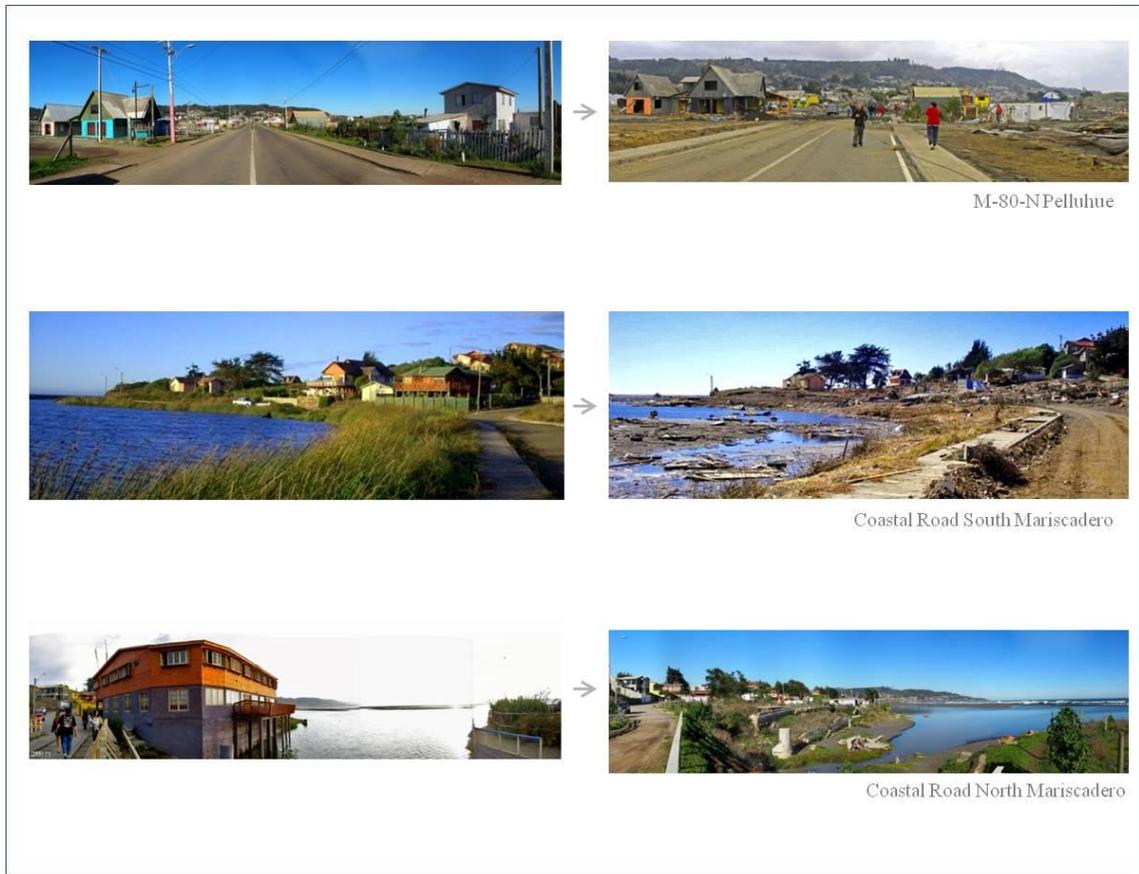


Figure 31: Road destruction after Tsunami
 Source: Felipe Iguait 2013.

B. Flood Analysis: Curanipe

In Curanipe the greatest damage occurred along the waterfront. The river edges of the Curanipe river and Parrón river were strongly affected, due to the low resistance of the natural river edges to tsunami waves. The fishing village was almost completely destroyed, as well as the health center and multipurpose sports field. The municipality building suffered widespread damage and recorded water depths up to 50 inches in the building. At the police station, located at the mouth of the river Curanipe, the water depth reached 70 inches inside the building. Over 50 houses in the coastal zone were destroyed

or rendered uninhabitable.⁵⁵ Damage to residences included damage due to floating debris, flooding, and foundation scour.

San Pedro Rock is the most crowded area during the summer in Curanipe town. It is located directly on the waterfront. The most important structural component in this place is a concrete retaining wall 120 meters long (400 ft) located on a north-south axis, and has a height of 4.5 meters. This wall separates the sands of east and west in order to allow the Curanipe's fisherman a presence on the east side of the wall. The wall had an important influence during the tsunami flood. 6,750 cubic meters of sand were displaced from the east side of the wall towards the interior of the town (Figure 33-34). The water of the two main rivers in Curanipe: Parrón and Curanipe river converge at this point. This was the principal water entrance into the city from tsunami waves. The water found least resistance at the beds of these rivers.

Next to San Pedro Rock is the camping area, with most of the fatalities in Curanipe. Also located in this camping area are the fisherman's boat place, storage, surfing area, traditional commerce, navigation in small boats, coastal footpath, pine forest, children's games, and facilities for resting. The south side of the San Pedro Rock sector was benefitted by the high topography of a marine bar, while the north was devastated due the low height produced by the erosion from the rivers. In the north of Curanipe, the damage was mainly focused in the conventional dwellings (Figure 37-38).

⁵⁵ "Estudio de Prefactibilidad Mejoramiento Borde Costero Curanipe Pelluhue, comuna Pelluhue, Región del Maule," ACUA, last modified May 5, 2011, http://dc254.4shared.com/doc/pGgi4aa_/preview.html

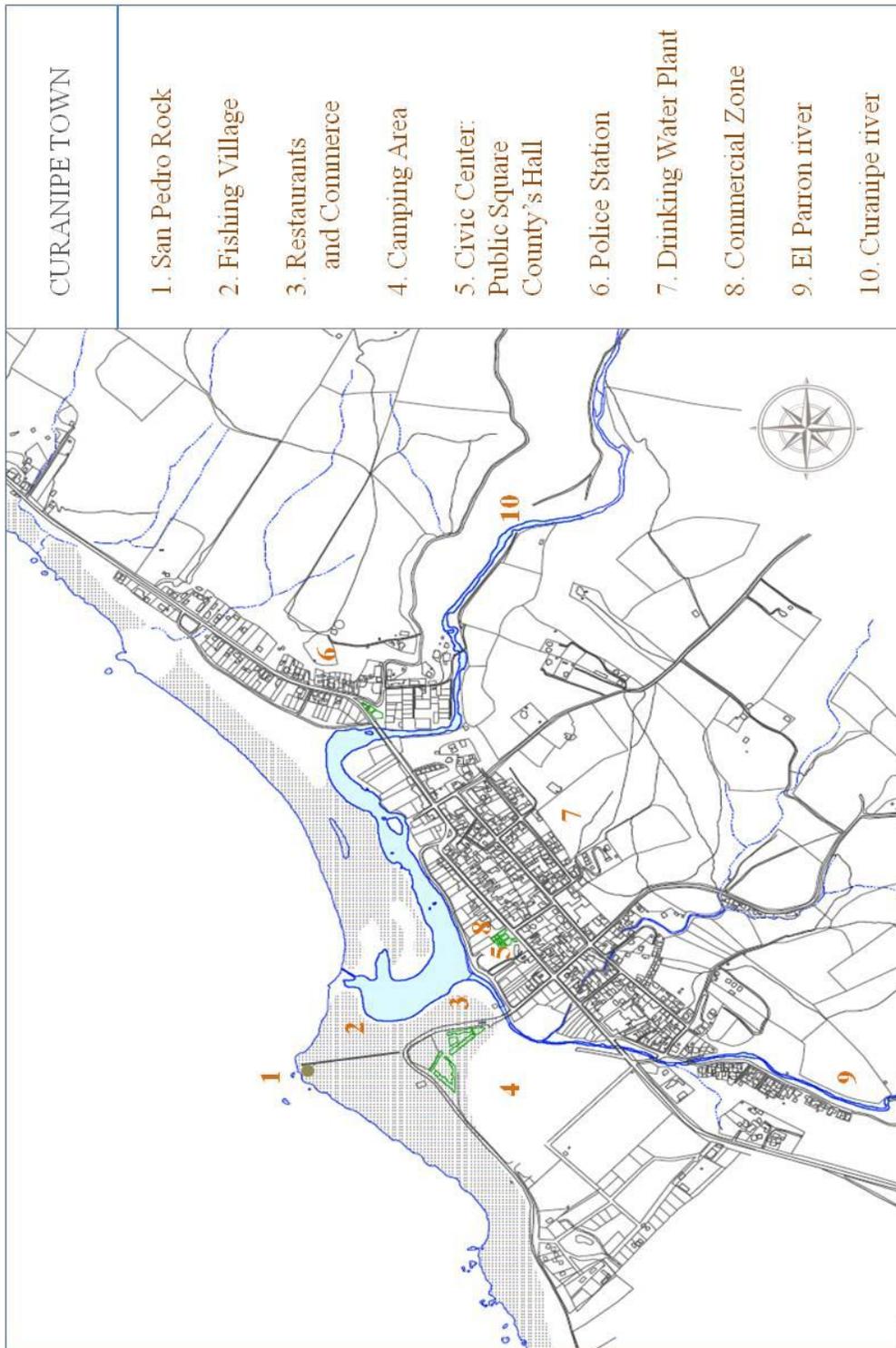


Figure 32: Curanipe Town Map
 Source: Felipe Igualt 2013.

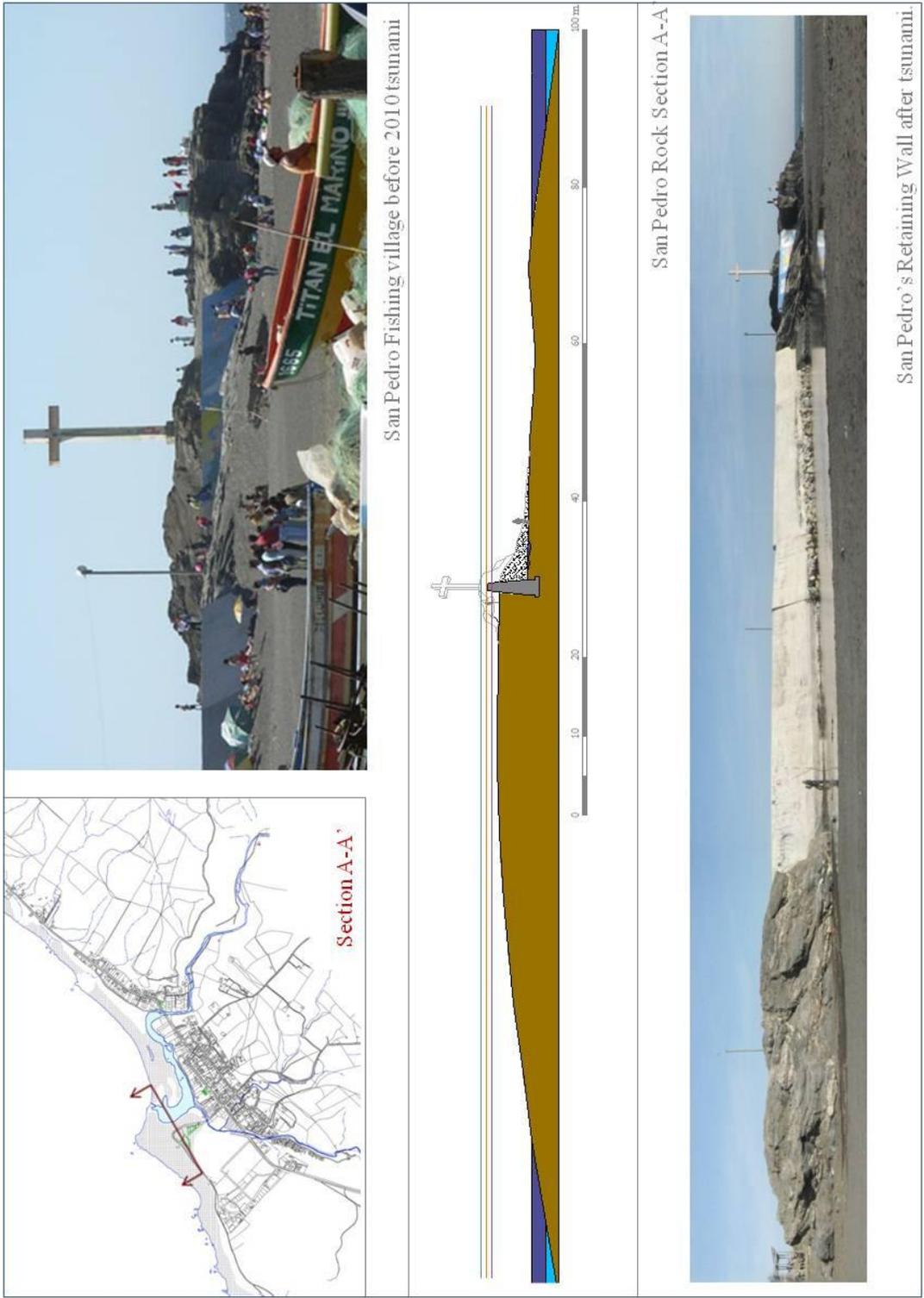


Figure 33: San Pedro Rock Analysis
 Source: Felipe Igualt 2013.

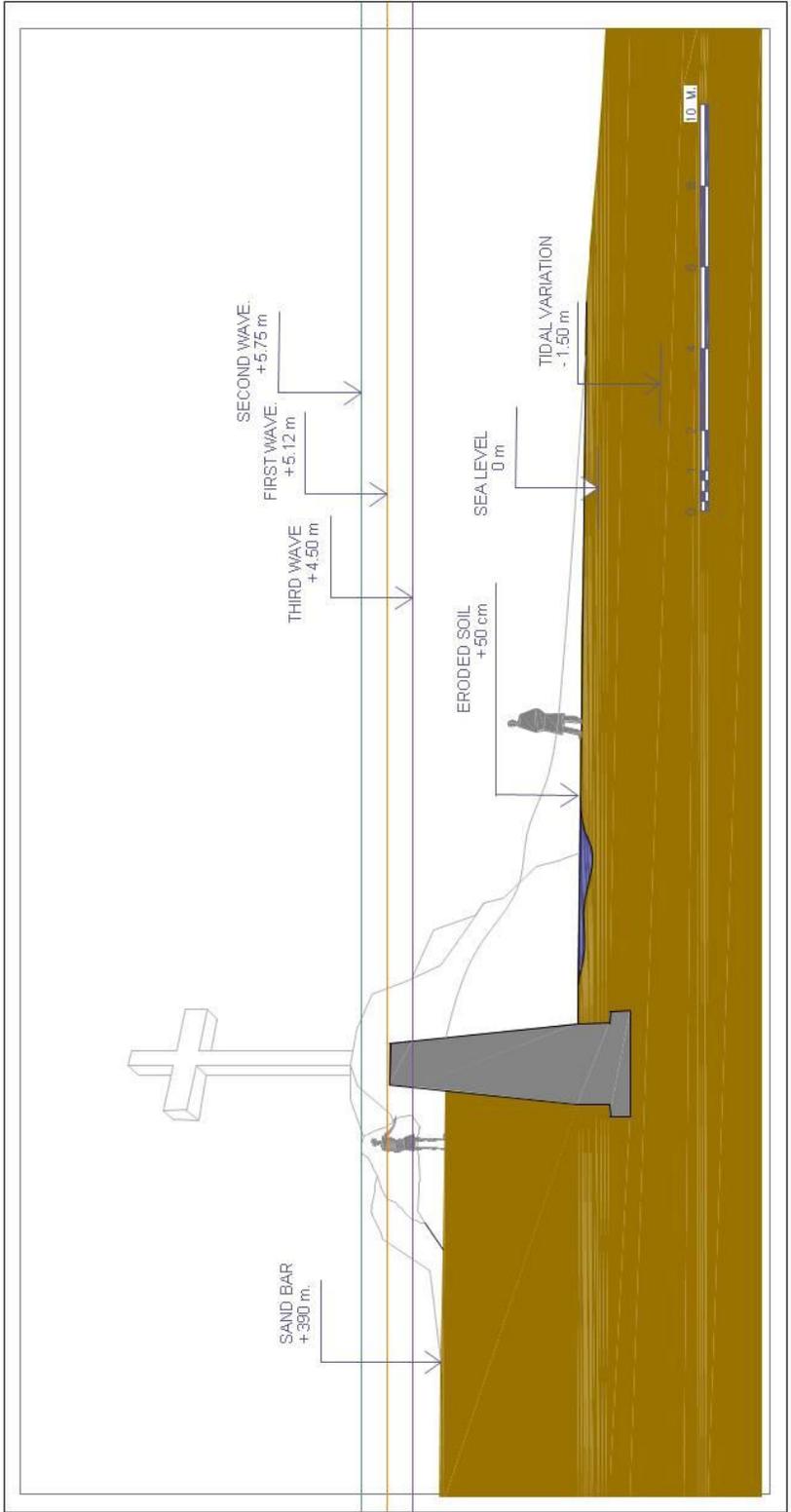
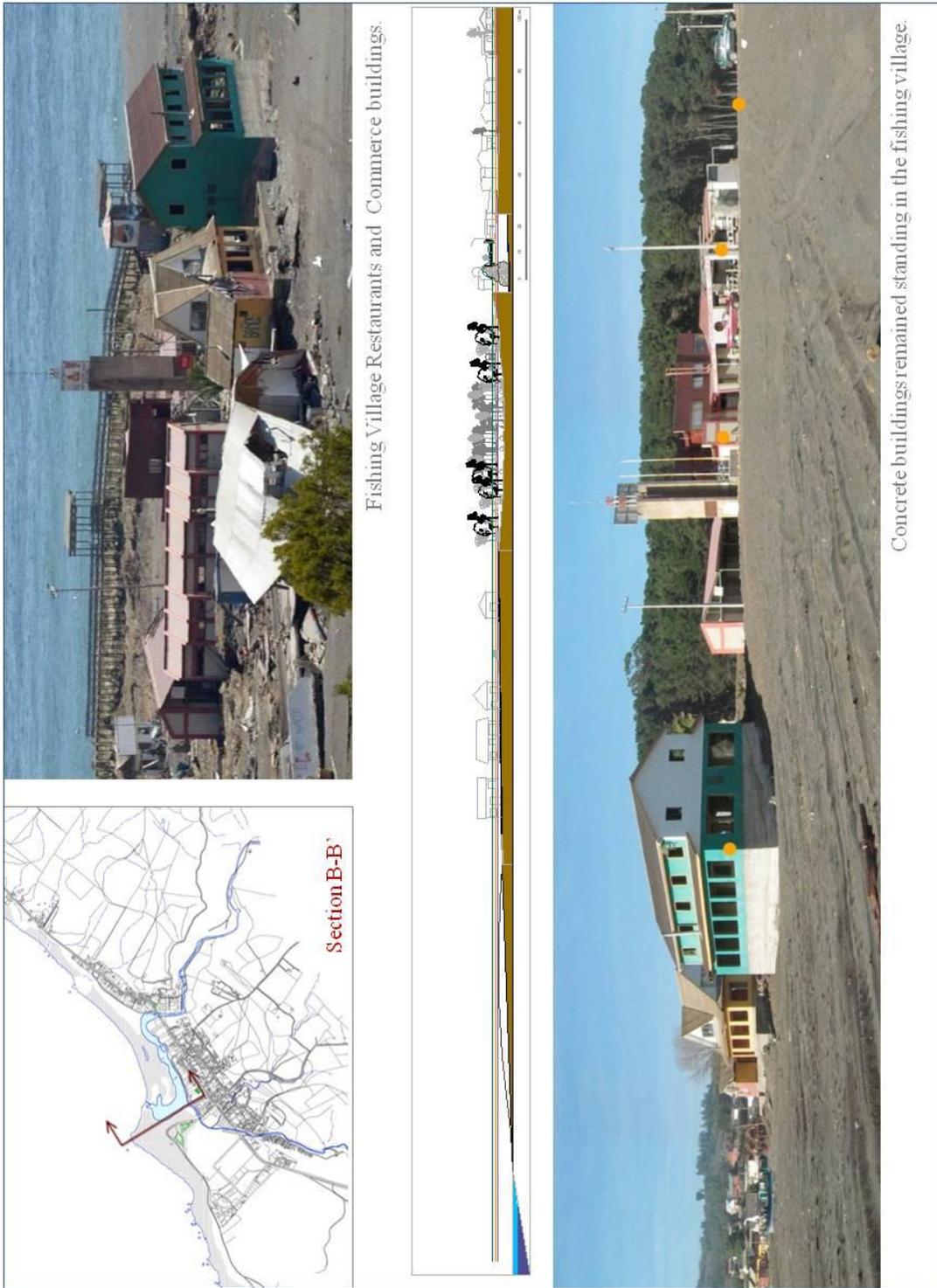


Figure 34: San Pedro Retaining Wall / Flood section
 Source: Felipe Igualt 2013.



Fishing Village Restaurants and Commerce buildings.

Concrete buildings remained standing in the fishing village.

Figure 35: Fishing Village Curanipe
Source: Felipe Igualt 2013.

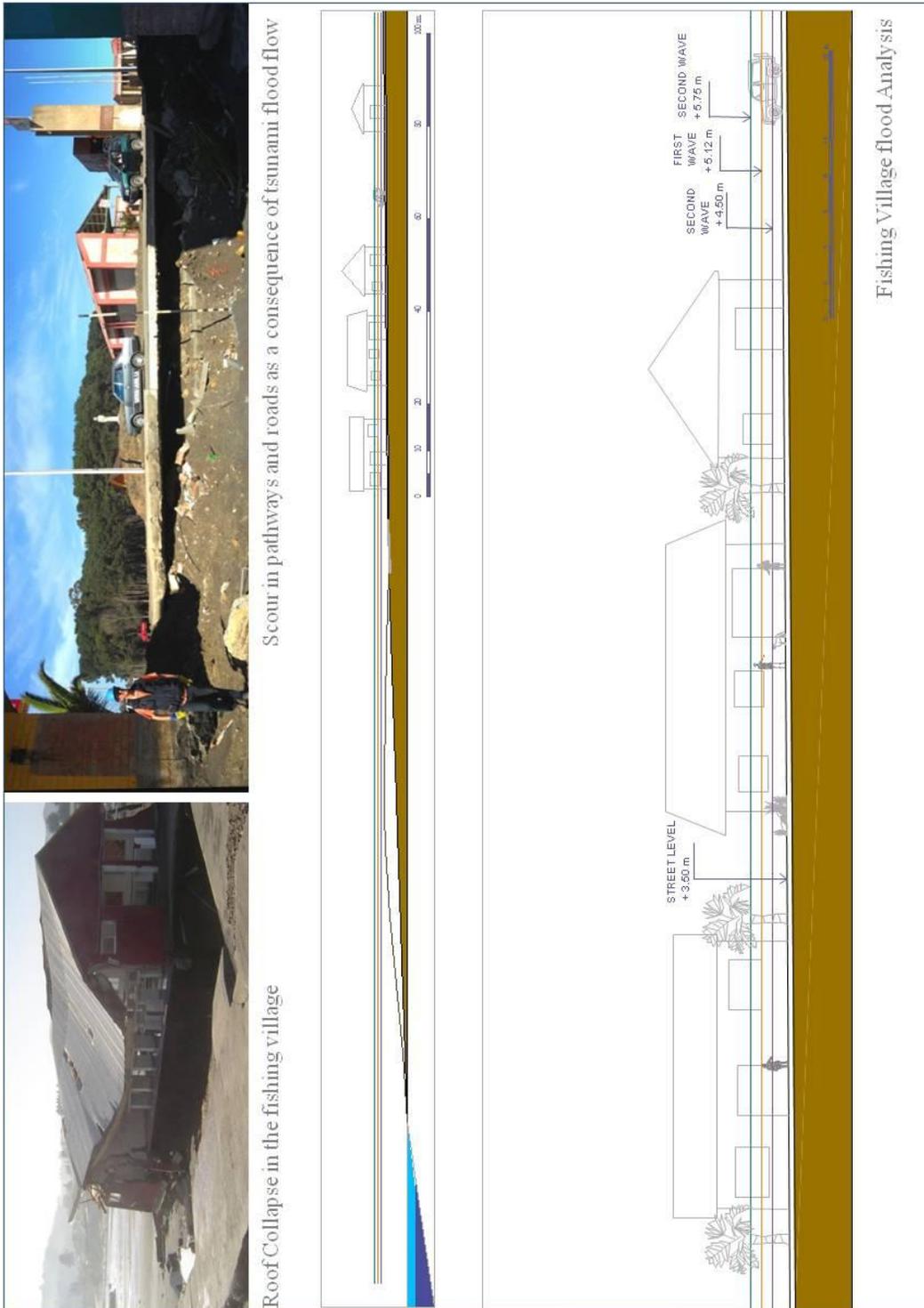
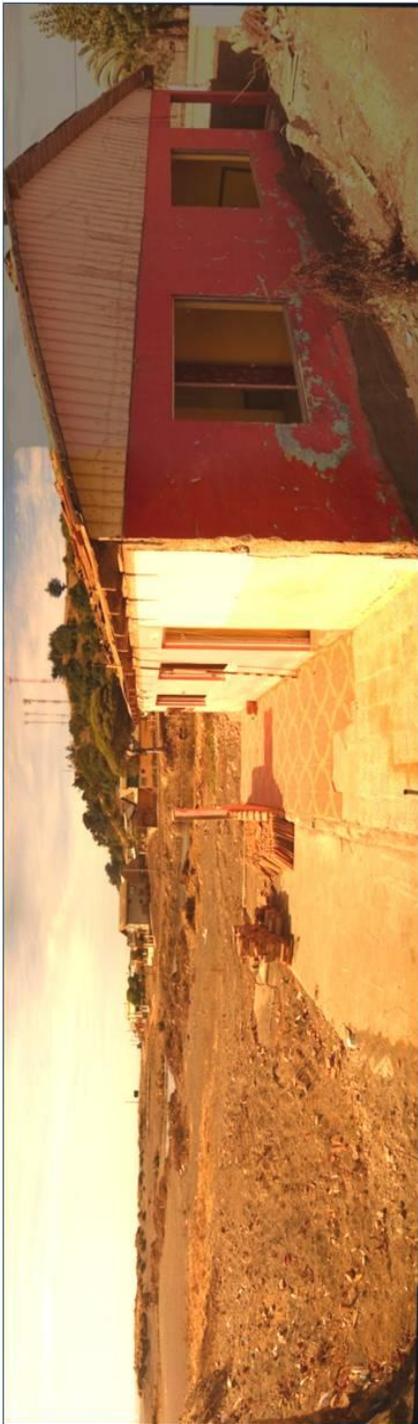


Figure 36: Fishing Village Curanipe
 Source: Felipe Igualt 2013.



Figure 37: Curanipe North Area
Source: Felipe Igualt 2013.



Masonry – Timber House affected by tsunami flood.

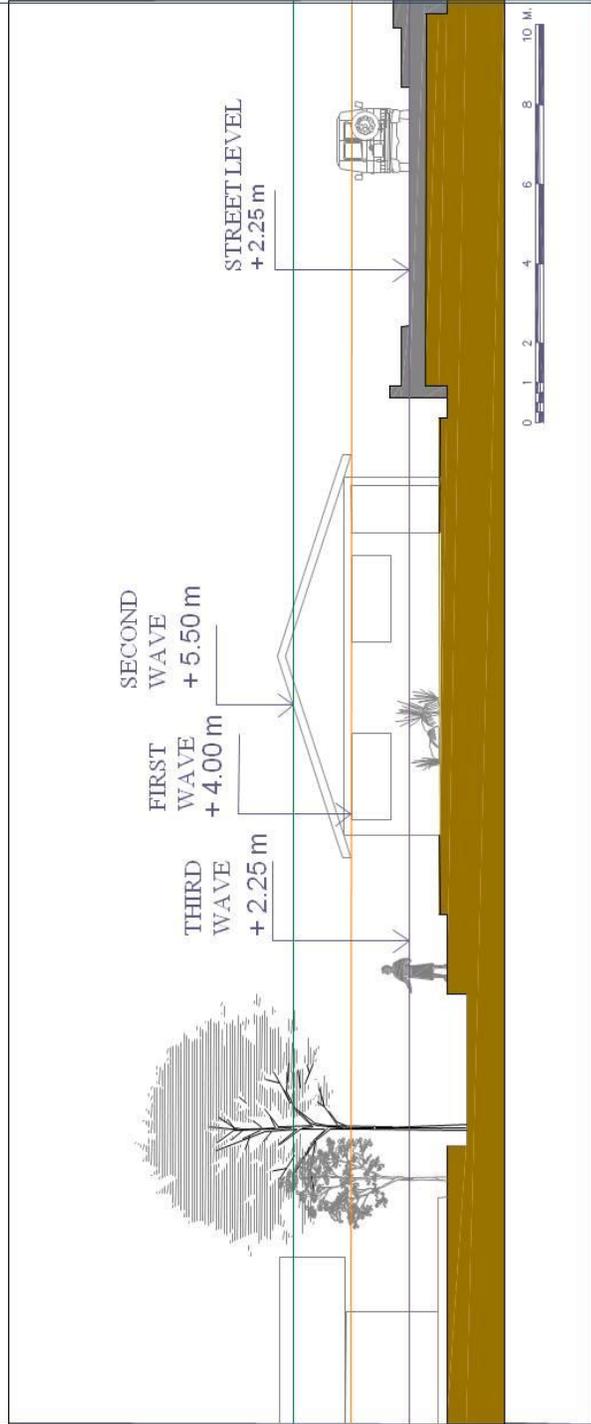


Figure 38: Curanipe North Area Dwellings
Source: Felipe Igualt 2013.

C. Flood Analysis in Pelluhue - Mariscadero

The affected public buildings were: the primary school, the fire station, the police station, and the municipal stadium. Also affected were the fresh water plant, the coastal road, and the Curanilahue Bridge, which connects the town to the northern cities. There was also a land rise of 1 meter in the fishing village area. This significant land rise made the fishing facilities inoperable.

The tsunami damage in the northern area of Pelluhue County, including Mariscadero town, was quite similar to the damaged incurred in Curanipe. In Pelluhue a larger number of residential buildings were affected due to their location in low lands, which were left exposed to the tsunami flood, especially in the river mouth of Curanilahue River. Due to this geographical situation in Pelluhue, the waterfront was not as affected as it was in Curanipe. However, dwellings located far from the coastline were strongly affected by tsunami flood. In Pelluhue a great number of public buildings were affected, along with public facilities located in the flood area.

As was the tendency along the affected coast, the flood drastically affected the timber structures. Most of the timber dwellings located in the flood area were totally destroyed. In the case of masonry structures, the situation was different depending on the location. Simple masonry dwellings located in the flooded area were damaged, while reinforced masonry structures were less affected. Masonry buildings didn't perform well when they were impacted by large debris.⁵⁶ The impact generated significant damage in simple masonry dwellings. Concrete buildings and structures had performed quite well in both earthquake and tsunami; however, most of the structures were affected by different degrees of adjacent scour.

Important urban service infrastructure was impacted in the risk zone. Even though this infrastructure had a fast recuperation after the tsunami, the population was without access

⁵⁶ Billy L. Edge, *Chile Earthquake and Tsunami of 2010* (Reston: American Society of Civil Engineers, 2013), 17-19.

to the main utilities such as water and electricity. The main road M-80-N was partially located in the risk area and was flooded and severely damaged in some areas. This increased the impact on the connectivity to outside the county after the tsunami.

Due to the ineffectiveness of M-80N road during and after the tragedy, the old road in the hills played a fundamental role in connecting Pelluhue County to outer areas. This shows the importance of maintaining the working order of this road throughout the whole year.

Mariscadero

Mariscadero area is located next to the north of Pelluhue. This town was also affected by the three tsunami waves. Again, the most destructive wave was the second, generating an average flood of 8.24 meters (27 ft). The higher run-up registered was 14.98 meters (48 ft) (Figure 44). A sand bar 8 meter high (26 ft) was located in front of Mariscadero, as well as a tree barrier, which partially protected the town from tsunami flood. The existing natural barrier comprised of low height sand dunes and artificial pine forest had a low impact in the flood mitigation.

This small town is very popular in summer due to the touristic demand. The settlement is located right in front of the beach and had a population of fishermen and seafood collectors. The material of the dwellings was mainly timber and resulted in total destruction. Only concrete buildings remained standing after tsunami flood. Even though the high flood affected Mariscadero, only one fatality was registered in this area. This is due to the strong connection of local people with the sea being able to identify the possibility of tsunami by reading the natural signals such as the earthquake intensity and the sea level retreating.

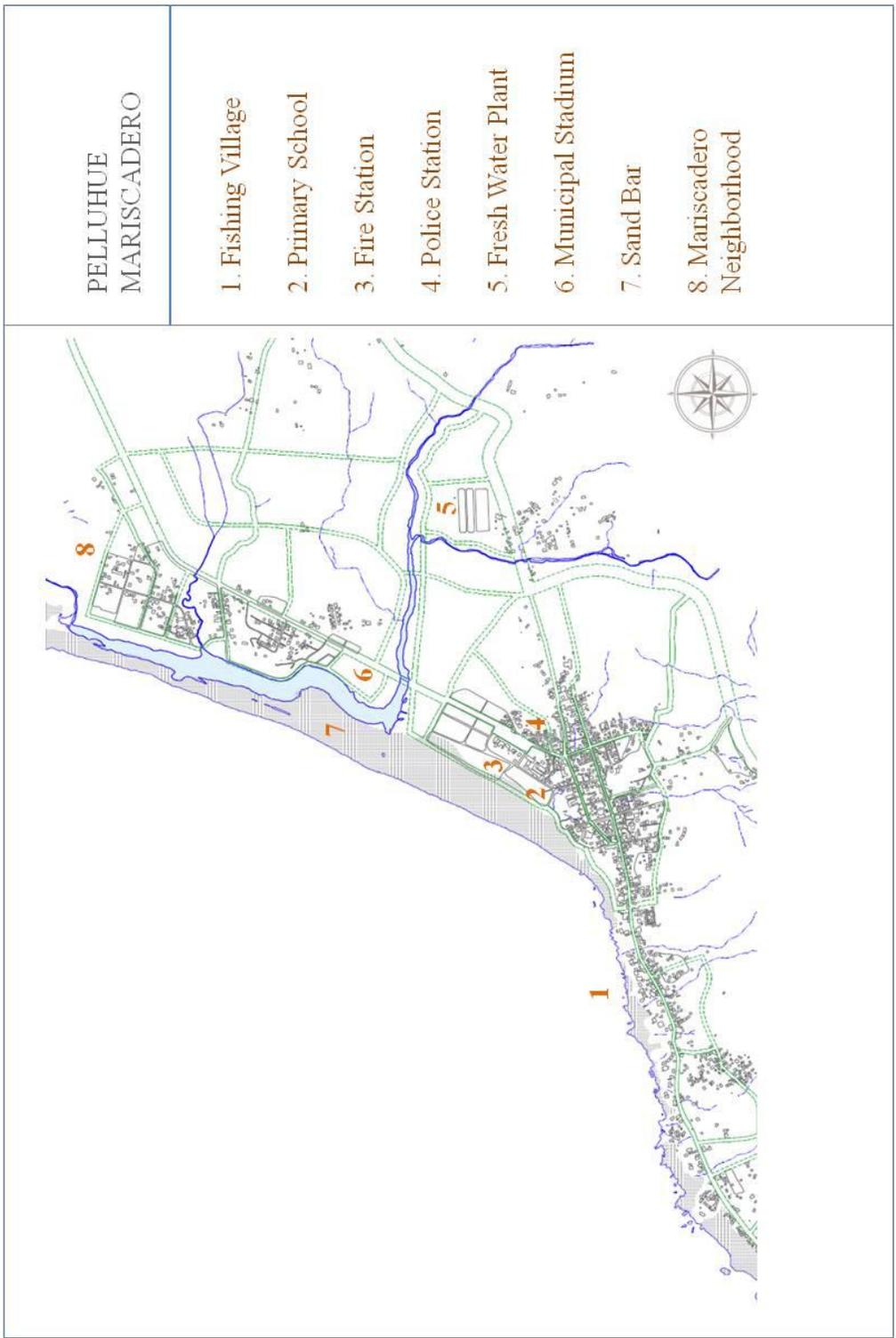


Figure 39: Pelluhue - Mariscadero Town Map
 Source: Felipe Igualt 2013.

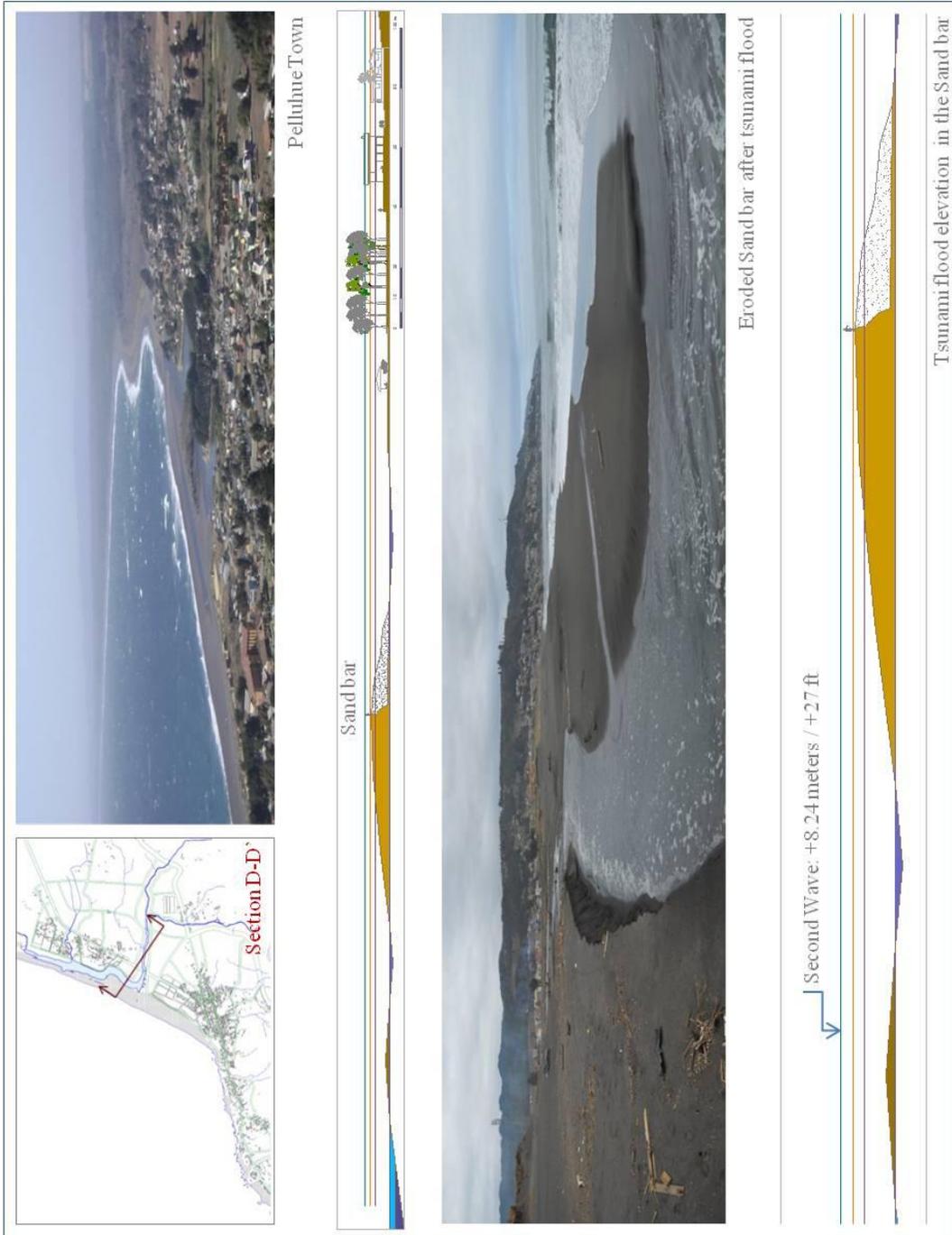
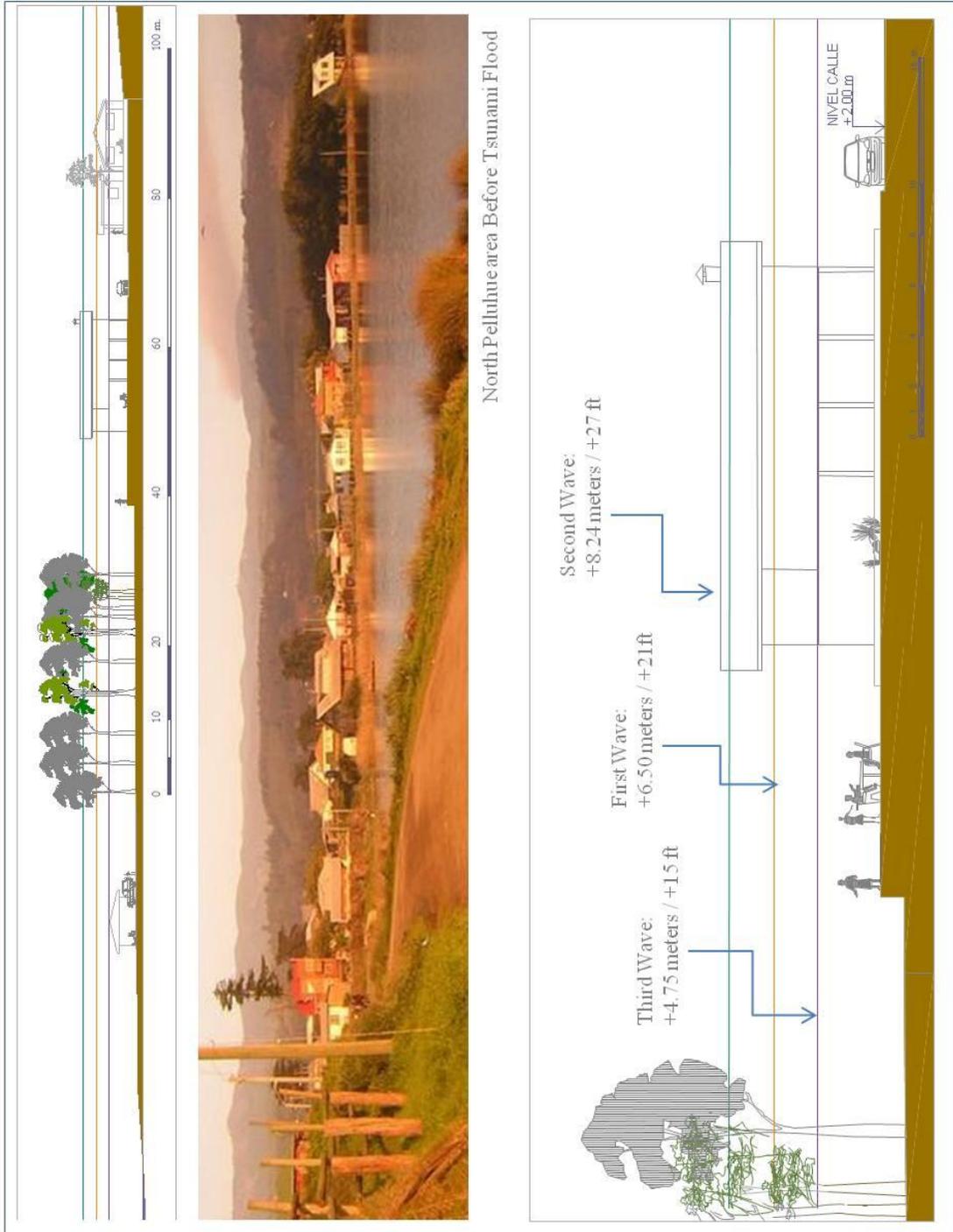


Figure 40: Pelluhue - Mariscadero Flood Analysis
 Source: Felipe Igualt 2013



North Pelluhue area Before Tsunami Flood

Figure 41: North Pelluhue - Dwelling Flood Analysis
Source: Felipe Igualt 2013



Figure 42: Tsunami Damage in Pelluhue - Mariscadero
 Source: Felipe Igualt 2013

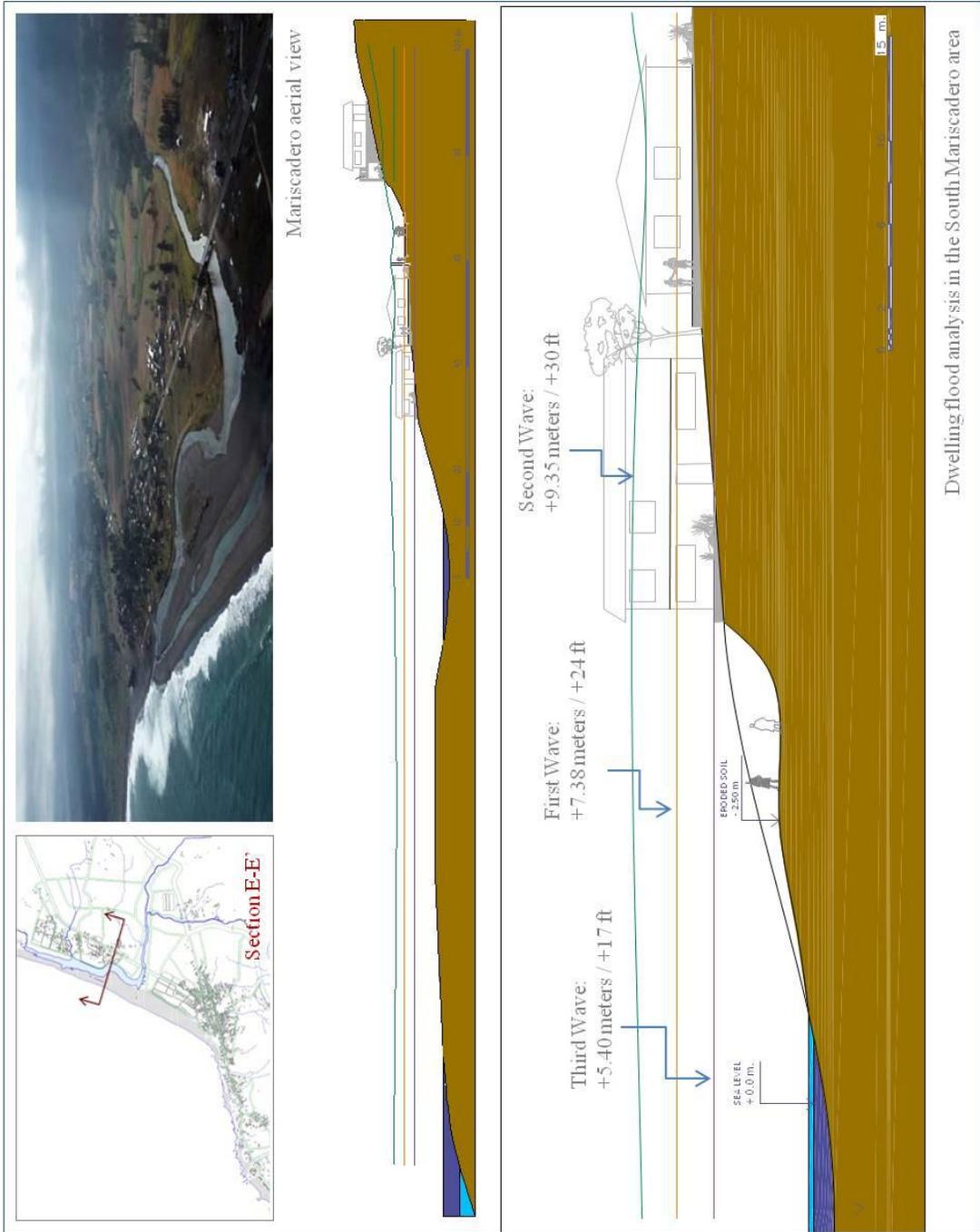


Figure 43: Flood Analysis in South Mariscadero
 Source: Felipe Iguait 2013

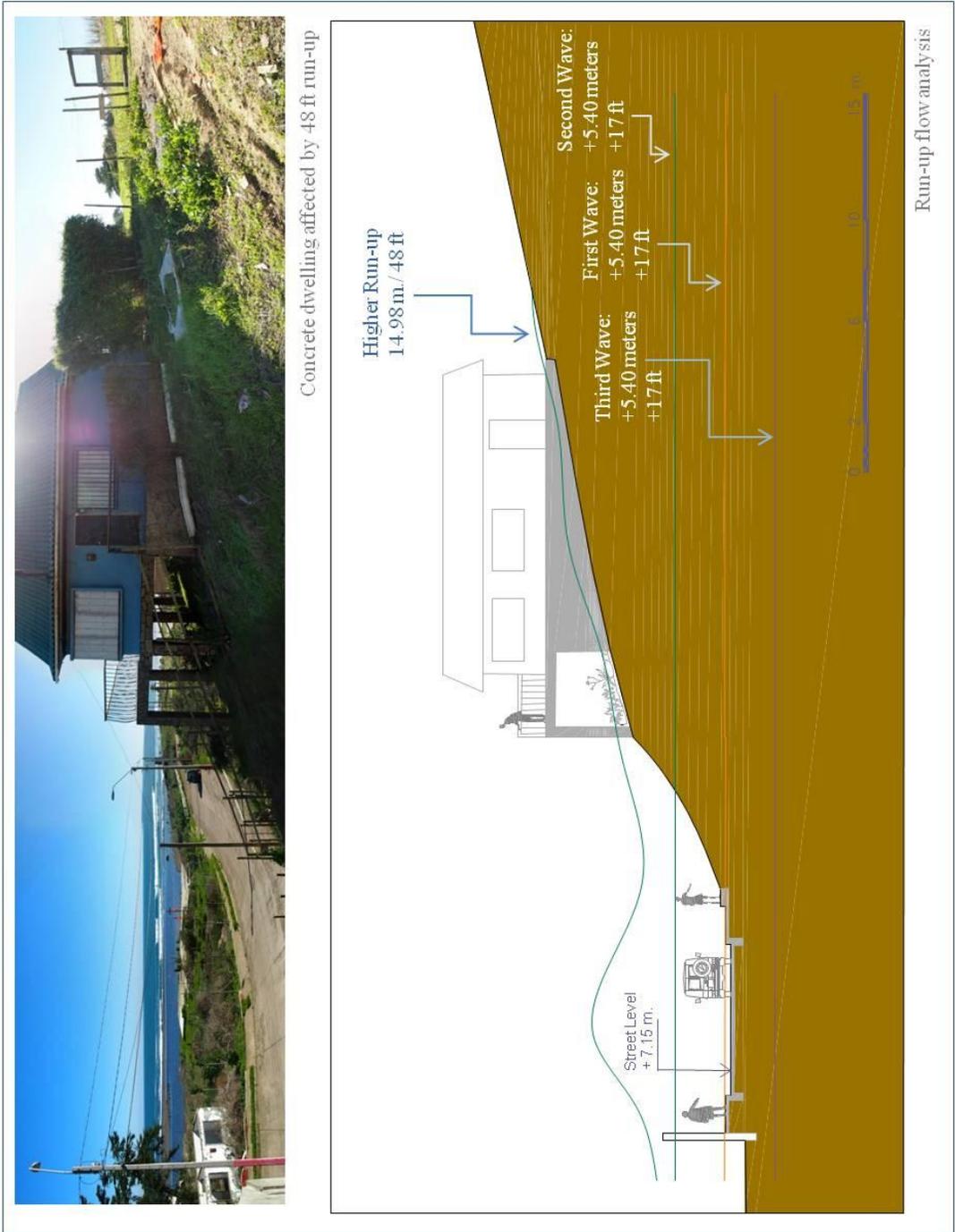


Figure 44: Run-up Mariscadero
Source: Felipe Igualt 2013



Figure 45: Flood Analysis - North Mariscadero
Source: Felipe Igualt 2013

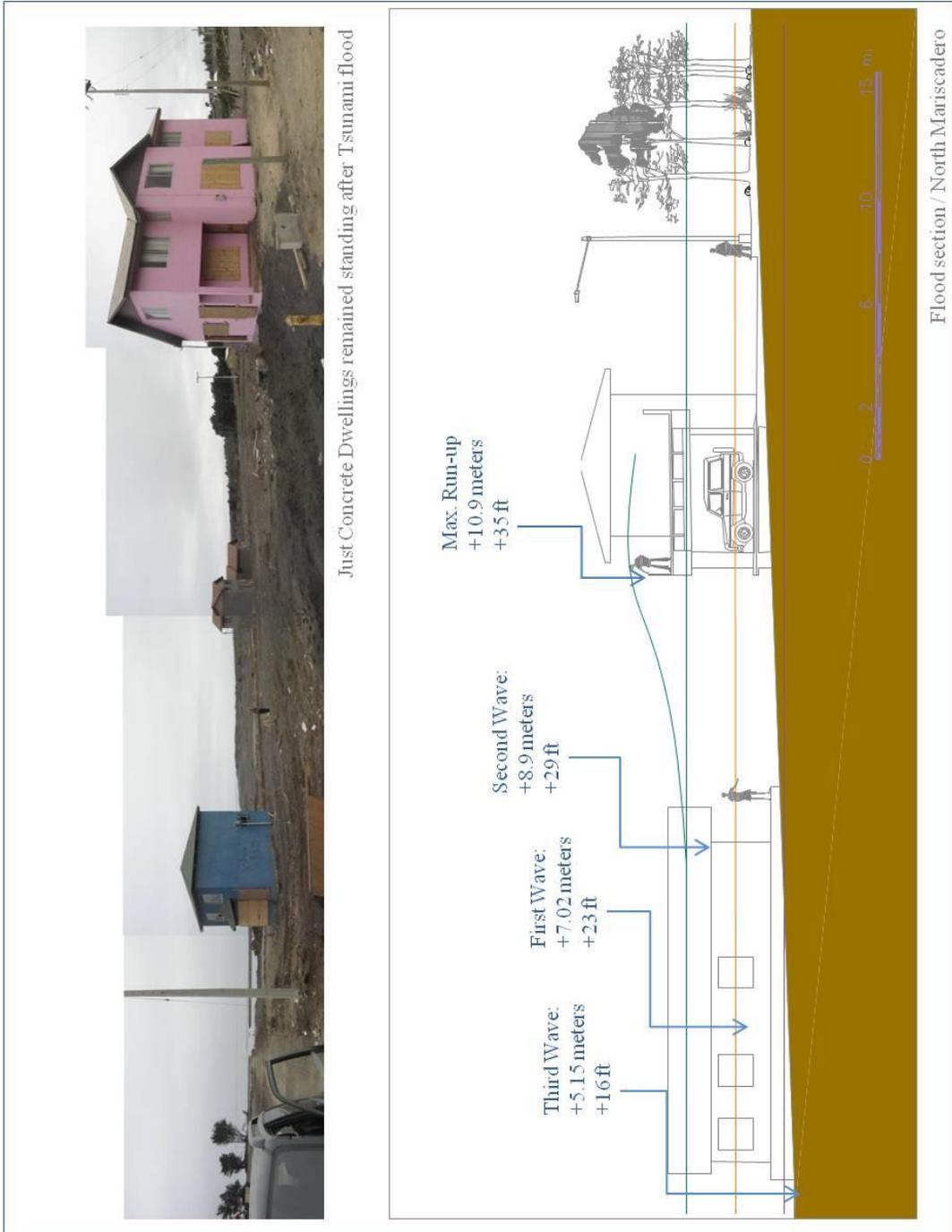


Figure 46: Flood Analysis - North Mariscadero Dwellings
 Source: Felipe Igualt 2013

Chapter V: Tsunami Damage in Coastal Structures and Case Studies

A. Coastal Structures and Tsunami Forces.

1. Coastal Structures

Coastal structures are mainly used for coastal defense, helping to prevent shoreline erosion and flooding of the hinterland. Other important functions of coastal structures are to provide protection to harbor basins and harbor entrances against waves. Coastal structures have a wide range of functions. Depending on their complexity, the function allows the essential coastal activities, from artisanal fishing to industrial harbor activity. Thus, coastal structures support important human activities, such as commerce and supply of food.

In this section, coastal structures will be separated in two categories: the conventional defensive coastal structures, and the natural protective structures.

a. Conventional defensive coastal structures.

i. Seawalls

The most predominantly used coastal structures are the seawall or tsunami seawalls. They are onshore structures whose principal function is to prevent, or to alleviate, overtopping and flooding of the land and the structures by storm surges and waves.⁵⁷ Tsunami seawalls are aligned along the shoreline and are made of concrete units that reach 10 meters high (32 ft). In contrast, tsunami walls (barriers) are located onshore and usually are built to separate the inner port-harbor facilities from the town structures further inland. These walls are also made mainly of concrete, and they are usually 5 to 10 meters high (16 to 32 ft). Tsunami seawalls also include steel gates, which provide vehicular and

⁵⁷ "Coastal engineering manual, Types and function of coastal structures," last modified November 11, 2013, http://140.194.76.129/publications/eng-manuals/EM_1110-2-1100_vol/PartVI/cem-vi-2.pdf

pedestrian access between the inner harbors and towns. These steel doors are closed during a tsunami event.⁵⁸

Erosion of the beach profile, landward of a seawall, can be stopped or at least reduced by seawalls. However, erosion of the seabed immediately in front of the structure is increased due to wave reflection caused by the seawall. Because of their potential vulnerability to toe scour, seawalls are often used together with some systems of beach control, such as groins and beach nourishment.⁵⁹

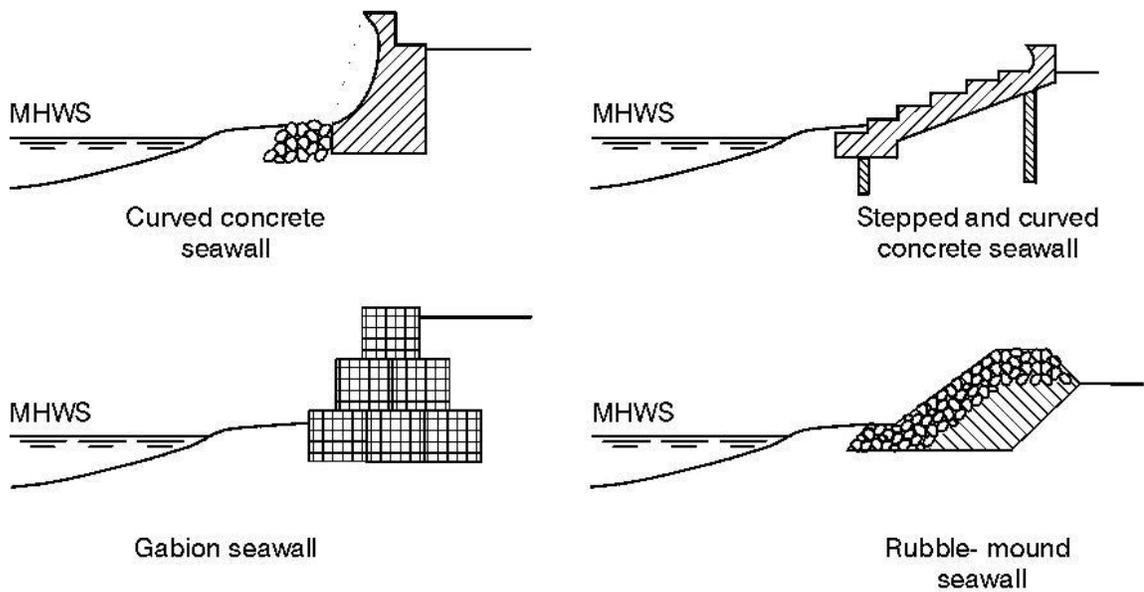


Figure 47: Examples of seawall structures
Source: Coastalwiki⁶⁰

⁵⁸ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 36.

⁵⁹ "Coastal engineering manual, Chapter 2, Types and function of coastal structures," last modified November 11, 2013, http://140.194.76.129/publications/eng-manuals/EM_1110-2-1100_vol/PartVI/cem-vi-2.pdf

⁶⁰ "Seawall Structures," last modified January 2014, http://www.coastalwiki.org/w/images/4/4f/Seawall_structures.jpg

ii. Sea Dikes or Coastal Dikes

Sea dikes are onshore structures whose principal function is to protect low-lying areas against flooding. These structures are typically constructed parallel to the shoreline to protect the coastal areas from tsunami waves, storm surges, typhoons, and high waves. Dikes built along large river basins also serve as flood control during tsunamis. Most of the coastal and river dikes are sloped in both seaward and landward faces (Figure 48). The seaside slope is usually very gentle in order to reduce wave run-up and damage produced by wave impact. The seaward slope is armored against damage from direct wave action. The faces are made of a packed earthen core covered with precast concrete slabs, pavers, or stone.⁶¹

The dikes usually range in size from approximately 5 to 20 meters (15-65 ft) wide at the base. Their crests generally consist of either asphalt topping or a concrete deck. Sea dikes are low-permeability structures protecting low-lying areas against flooding. As a consequence, fine materials such as sand, silty sand, and clay are used for the construction.⁶² Usually, the structures are designed based on the flood registers obtained during the most catastrophic events affecting the coastal areas. In this way, when the historic mark is exceeded, the sea dike should be redesigned to satisfy the new flood elevation.

⁶¹ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 36.

⁶² "Coastal engineering manual, Chapter 2, Types and function of coastal structures," last modified November 11, 2013, http://140.194.76.129/publications/eng-manuals/EM_1110-2-1100_vol/PartVI/cem-vi-2.pdf

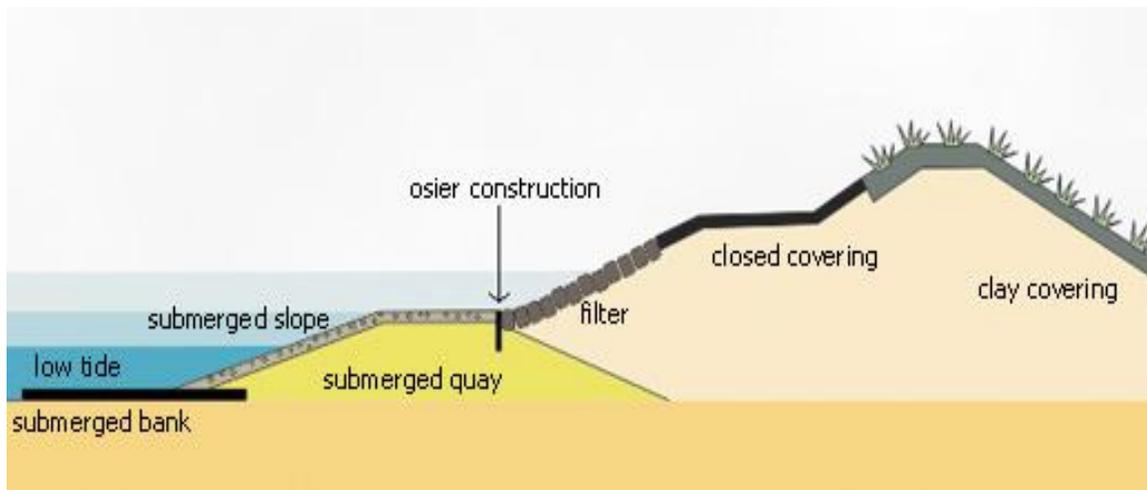


Figure 48: Sea Dike Cross Section
 Source: SeaOnScreen⁶³

iii. Breakwater

Breakwaters are built to reduce wave action in an area in the lee of the structure. Wave action is reduced through a combination of reflection and dissipation of incoming wave energy. When used for harbors, breakwaters are constructed to create sufficiently calm waters for safe mooring and load operations, handling of ships, and protection of harbor facilities. Breakwaters are also used to improve maneuvering at harbor entrances or fishing villages. These structures help also to regulate sedimentation by directing currents and by creating areas with different levels of water disturbance.⁶⁴

Breakwaters are mostly sloped in front, but there are also vertical front structures. Sloping front structures are, in most cases, rubble-mound structures armored with rock or concrete armor units, with or without wave wall structures (Figure 49). Vertical front

⁶³ "Sea Dikes," last modified May 15, 2014, <http://www.zeeinzicht.nl/vleet/index.php?id=4298&template=template-vleeteng&language=2&item=Sea-dikes>

⁶⁴ "Coastal engineering manual, Chapter 2, Types and function of coastal structures," last modified November 11, 2013, http://140.194.76.129/publications/eng-manuals/EM_1110-2-1100_vol/PartVI/cem-vi-2.pdf

structures are, in most cases, constructed of either sand filled concrete caissons or stacked massive concrete blocks placed on a rubble stone-bedding layer (Figure50).⁶⁵

Offshore breakwaters constructed across harbor entrances can be very effective in protection of shoreward port areas from a tsunami. Japanese breakwaters typically consist of massive precast concrete caissons on top of a rubble mound base. Precast concrete units such as tetrapods, dolos, or otherwise engineered concrete units, usually armor the seaward side of a breakwater. The cost of a breakwater increases significantly with water depth and wave severity. Poor foundational conditions also increase cost. These three environmental factors heavily influence the design and positioning of the breakwaters and the harbor or fishing village layout.

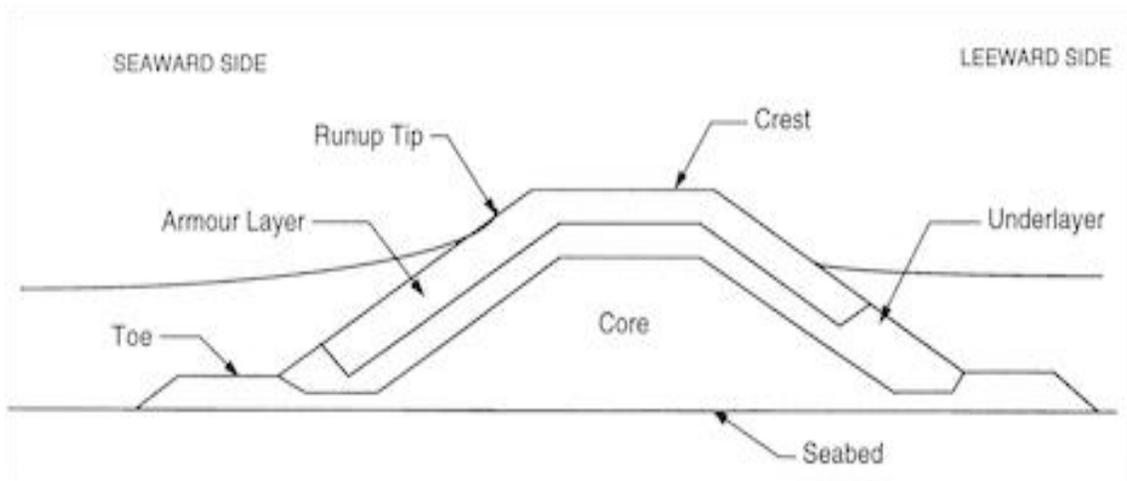


Figure 49: Cross section of sloping front breakwater
Source: University of Wisconsin Madison⁶⁶

⁶⁵ "Coastal engineering manual, Chapter 2, Types and function of coastal structures," last modified November 11, 2013, http://140.194.76.129/publications/eng-manuals/EM_1110-2-1100_vol/PartVI/cem-vi-2.pdf

⁶⁶ "Analysis of the Wave Energy Reduction of Rubble Mound Breakwaters," last modified January 5, 2014, <http://universitywimadisonbreakwater.weebly.com/objective-and-background.html>

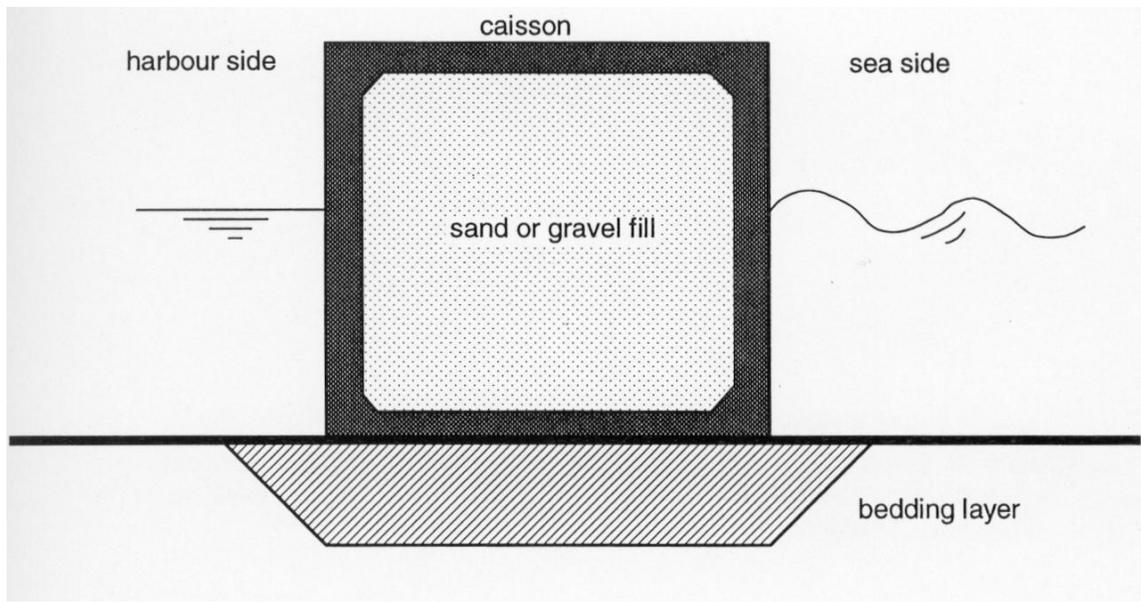


Figure 50: Cross section of vertical front breakwater
Source: Kennisbank⁶⁷

iv. Mechanisms for damage and failure

Natural and artificial coastal structures can react differently after a tsunami flood affects them. The degree of damage depends of a set of conditions, from the proximity with the epicenter to the quality of materials used in the coastal structure. The placement and orientation, as well as quality of soils of the structures are relevant to understanding the cause of damage.

⁶⁷ "PIANC Open Teaching Material," last modified January 5, 2014, <http://www.kennisbank-waterbouw.nl/EC/CLM01060002.html>

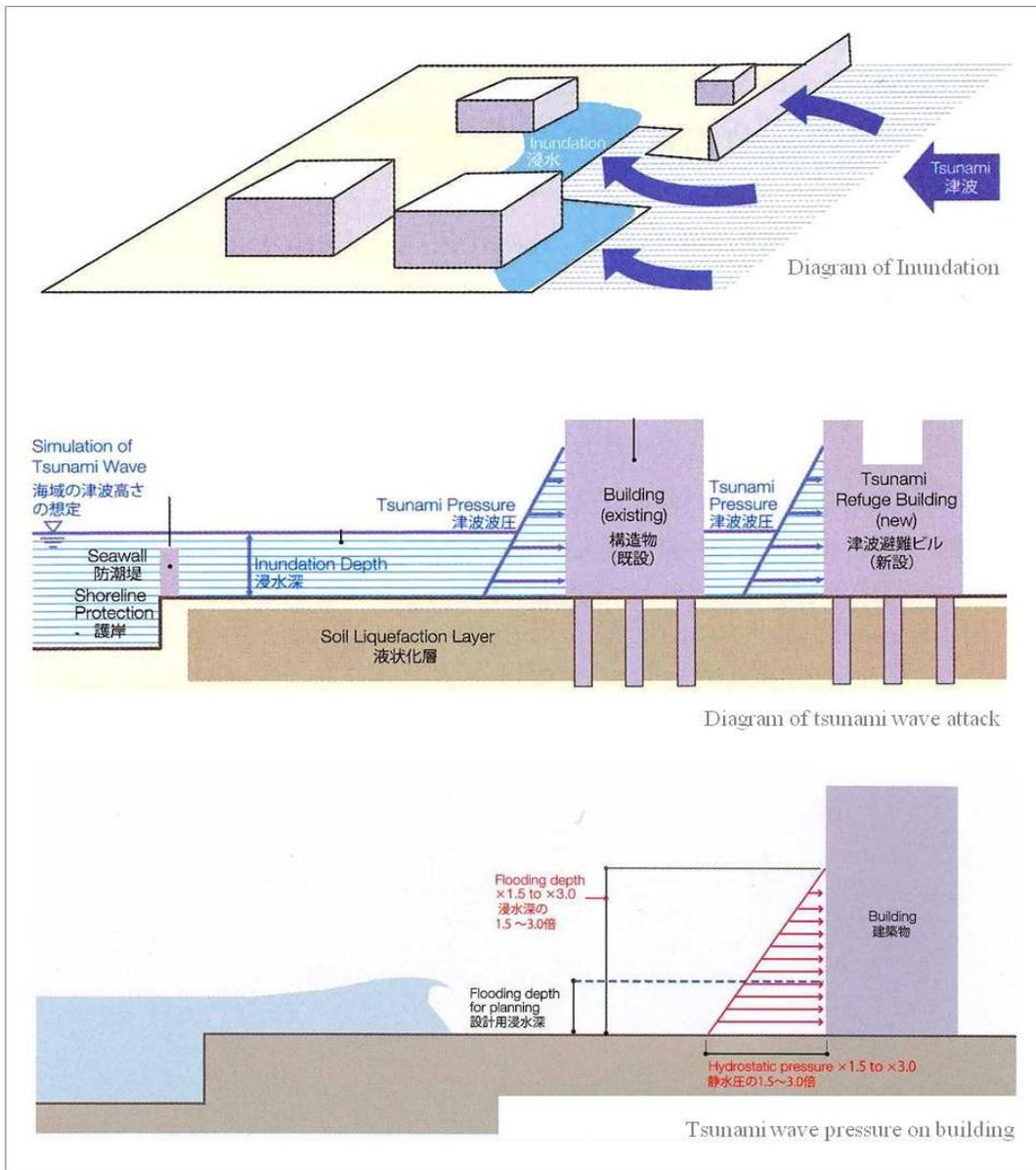


Figure 51: Tsunami Flood Analysis
 Source: a+u magazine ⁶⁸

Many structural failures occur due to multiple mechanisms. For example, some of the coastal dike failures most likely started when overtopping and uplift forces removed some of the concrete panels from the inland depth side of the earthen berm. Continued

⁶⁸ Yoshida, Nobuyuki, and Kabushiki Kaisha Sekkei, "Face to face with nature: cities, architecture, people," A+U, August 2012.

overtopping then scoured the earthen fill, reducing or removing the lateral support for the seaward portion of the wall. Complete collapse occurs either when tsunami forces remove critical lateral supports or when an impact load exceeds resisting forces. Such failures result from the combination of overtopping, uplift forces, and impact loads rather than from a single cause.⁶⁹

Tsunami Uplift Forces

When tsunami waves completely or partially submerge a structure, or when they pass underneath a structure, the result is entrapment of the waves on the underside of the structure. Then, the structures experience uplift forces due to the hydrostatic buoyancy including effects of excessive pressure and hydrodynamic forces. The uplift forces reduce the structure's total effective dead weight, which may affect the structure's resistance to overturning and sliding. Excessive tsunami-induced uplift forces can lift a structure from its foundation, especially when the structure does not have sufficient anchorage (Figure 52).⁷⁰

Impact loads constantly affect coastal tsunami structures during inundation. Forces include unsteady hydrodynamic drag forces, impulsive forces, debris impact forces, and debris damming forces. Water flowing around a structure applies hydrodynamic drag forces to the structure. These forces are a combination of the lateral forces caused by the pressure forces from the moving mass of water and the friction forces generated as water flows around structure.⁷¹

⁶⁹ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 44.

⁷⁰ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 50.

⁷¹ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 36.

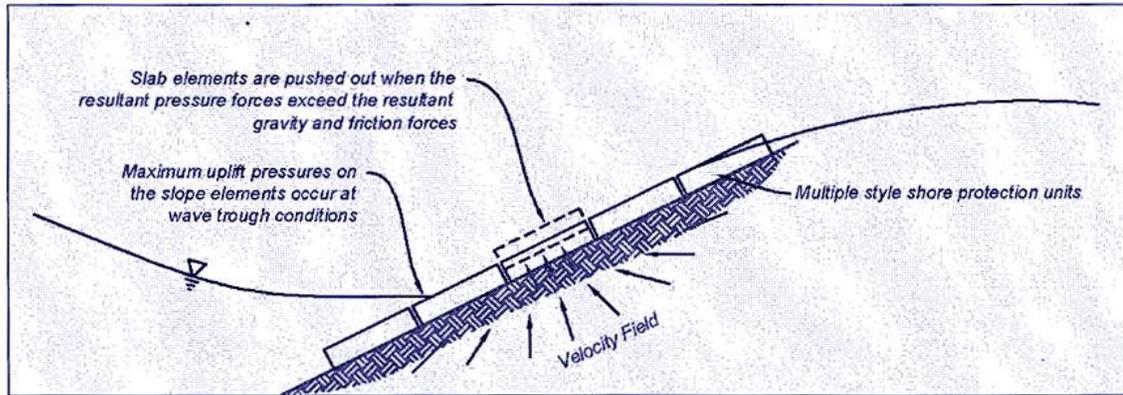


Figure 52: Hydrostatic Uplift Forces
 Source: American Society of Civil Engineers ⁷²

Scour

The removal of earthen sediments and vegetation by the incoming tsunami wave run-up, as well as the subsequent seaward draining of the floodwaters, generates unusually high stream flow velocities and turbulence. Soil erodes quickly when the aerodynamic flow conditions exceed soil threshold conditions. Erosion occurs often at the inland base or toe of the structures when it is overtopped by tsunami inundation. In tsunamis, scour is especially prevalent at structural corners and areas of flow convergence (Figure 53). ⁷³

Beach erosion, and erosion around the exposed foundation of coastal structures, result from sediment scouring caused by the incoming tsunami wave's high water velocities, water turbulence, and superficial flows during the tsunami's run-up and backrush due to the large flux of displaced water and the high energy involved (Figure 54).

⁷² Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 50.

⁷³ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 57-59.

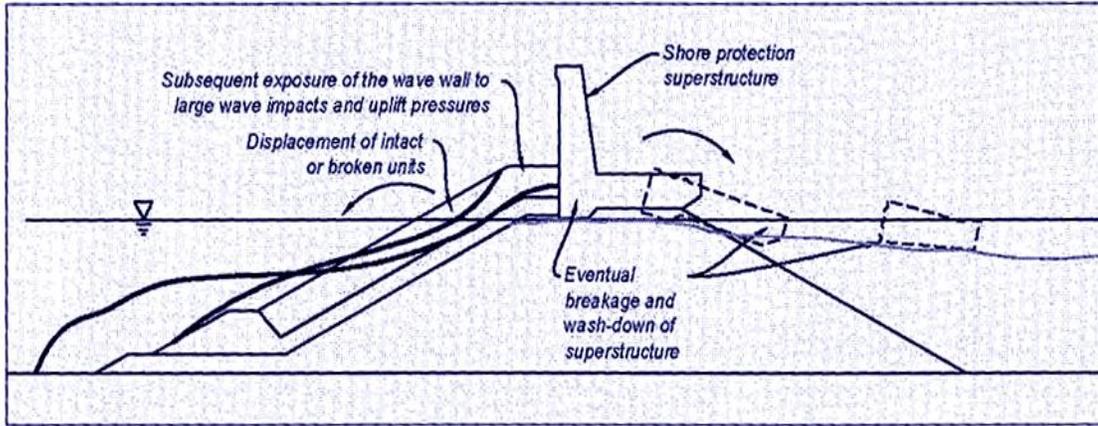


Figure 53: Diagram of Scour Mechanisms
 Source: American Society of Civil Engineers ⁷⁴

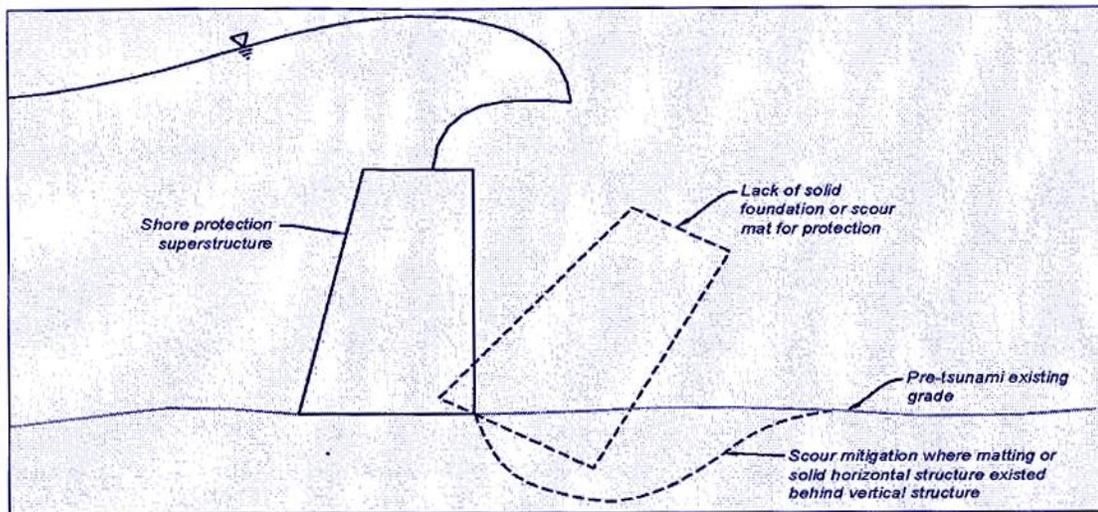


Figure 54: Erosion Diagram
 Source: American Society of Civil Engineers ⁷⁵

⁷⁴ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 58.

⁷⁵ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 61.

b. Natural protective structures.

Nature contains landscape elements that can be used as a protective barrier against natural disasters. In Japan, forested green belts have been developed to mitigate coastal hazards such as sandstorm, salty winds, high tides, and tsunamis. Even though natural strategies of protection are less effective against tsunami flood than the conventional defensive coastal structures, they can prove extremely effective when both typologies are combined. Among the wide range of natural protective structures, the two main strategies used are greenbelts and dune construction with beach nourishment.

i. Greenbelts or Vegetative Barrier

Green belts can be effective against small tsunami floods, sea winds, or sands, but not against a huge tsunami like that of Japan 2011. Combining green belts with dikes and embankments can improve their effectiveness. Green belts reduce tsunami damage by reducing wave energy, delaying water arrival time, and protecting houses by capturing floating debris (Figure 55). Usually, natural structures provide a second or third line of defense.

Green belts also provide other important benefits recognized by communities, such as: protection from coastal storms, salt damage and sand, and provide spaces for recreation and wildlife. Forests may also provide psychological safety and augment a feeling of well-being. Green belts require several decades to develop properly. Local communities can play important roles in green belt maintenance.⁷⁶

⁷⁶ "Green Belts and Coastal Risk Management," last modified November 11, 2013, http://wbi.worldbank.org/wbi/Data/wbi/wbicms/files/drupal-acquia/wbi/drm_kn2-8.pdf

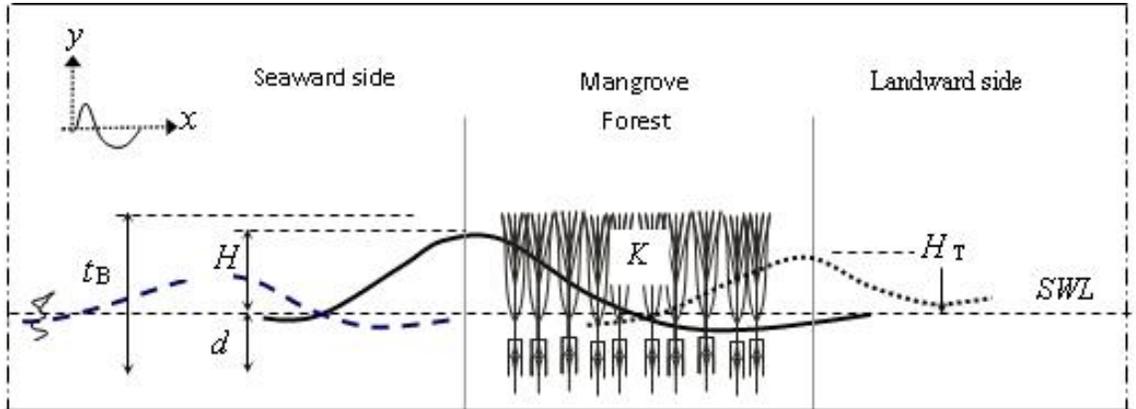


Figure 55: Mangrove Forest Sea Belt.
Source: Disaster Reduction Hyperbase ⁷⁷

ii. Use of green belts as a tsunami barrier

Field investigations after the huge tsunami in the Indian Ocean in 2004 suggest that establishing or strengthening greenbelts of mangroves, and other coastal forests, may play a key role in reduction of the effect of future catastrophic events. This suggestion comes from the simple observation that those localities surrounded by mangrove forests were less affected than those localities without mangrove forests. Therefore, green belts that utilize coastal vegetation together with other natural features, such as sand dunes or lagoons, have been studied since they require relatively small capital investment compared to artificial measures. These methods also provide human-friendly beachfronts, and enhance inter-relationships with other ecological systems.⁷⁸

⁷⁷ "Mangrove Forest," last modified January 10, 2013, <http://drh.edm.bosai.go.jp/files/5ceb0071988a1dca226b3b41028af03fa159a9b6/Figure-1.jpg>

⁷⁸ "Effectiveness and Limitations of Vegetation Bioshield in Coast for Tsunami Disaster Mitigation," Norio Tanaka, last modified October 25, 2013, http://cdn.intechopen.com/pdfs/13082/InTech-Effectiveness_and_limitations_of_vegetation_bioshield_in_coast_for_tsunami_disaster_mitigation.pdf



Figure 56: Defensive Green Belt in Oki Bay, Kochi Prefecture, Japan.
Source: FAO 2007⁷⁹

Inundation distances and patterns are affected by the shape, height, and surface of the land. These parameters are a function of the land coverage and use, in populated environments. Flatter topographies allow more widespread inundation and greater inland penetration, which results in a higher degree of destruction. In the same way, tsunami flow is able to penetrate a much greater distance when travelling over land that offers a low friction coefficient. In this context, the river mouths are strongly affected. In rivers, the friction coefficient is very low and the tsunami flow penetrates through the river course with little difficulty.⁸⁰

The protective nature of raised features dissipates wave energy, whether they are natural features such as sand dunes and beach ridges, or artificially grown coastal forests. However, it has been noted by several authors that if the vegetation fails, floating debris can cause more damage to the urban infrastructure. In the case of natural sand dune

⁷⁹ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827dddf4003076c480c.pdf>

⁸⁰ "GIS Evaluation of the Impacts on the Built and the Natural Environment of the 11 March 2011 Tsunami in Rikuzentakata, Iwate Prefecture, Japan," Christopher Gomez et al., last modified October 25, 2013, <http://hal.archives-ouvertes.fr/docs/00/65/50/23/PDF/Article-32-TechnicalReportRikuzentakata.pdf>

systems, large tsunamis commonly result in erosion of, or complete reorganization of, sandy barriers, drainage systems, and coastline structures.⁸¹

Floating debris from broken trees can damage the surrounding buildings and injure people. However, many studies have revealed that these detriments can be overcome with proper planning and management of coastal forests. These same studies suggest that coastal vegetation has a significant potential to mitigate damage in constructed areas and save human lives by acting as buffer zones during extreme natural events. However, the effectiveness of vegetation changes with the age and structure of the forest.⁸²



Figure 57: Extensive Control Forest in Ibagari Prefecture, Japan
Source: FAO 2007⁸³

⁸¹ "GIS Evaluation of the Impacts on the Built and the Natural Environment of the 11 March 2011 Tsunami in Rikuzentakata, Iwate Prefecture, Japan," Christopher Gomez et al., last modified October 25, 2013, <http://hal.archives-ouvertes.fr/docs/00/65/50/23/PDF/Article-32-TechnicalReportRikuzentakata.pdf>

⁸² "Effectiveness and Limitations of Vegetation Bioshield in Coast for Tsunami Disaster Mitigation," Norio Tanaka, last modified October 25, 2013, http://cdn.intechopen.com/pdfs/13082/InTech-Effectiveness_and_limitations_of_vegetation_bioshield_in_coast_for_tsunami_disaster_mitigation.pdf

⁸³ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

The use of coastal control forests is being analyzed, especially after the 2011 Japan tsunami. Recently, natural methods have become better understood. Their effectiveness depends on the magnitude of the tsunami and the type of vegetative structure.⁸⁴ One of the most advantageous features of coastal forests, over other typologies of coastal defense structures, is their capacity to allow a portion of the tsunami to pass through the forest, gradually attenuating its force. Conversely, a solid wall may be broken apart, lifted up, or overtopped.⁸⁵

iii. How coastal forest works as a tsunami barrier

The incorporation of tsunami forests, in locations affected by tsunamis, has been widely studied in the last decade, especially because they represent a low-cost natural mitigation measure with reduced urban impact. However, tsunami forests cannot be applied in any coastal location without careful study.

Tsunami forests need special conditions to grow, including organic material in the soil, fresh water, and good weather. In tropical locations, such as Southeast Asia, mangrove forests are appropriate tsunami forests. In a temperate and humid continental climate, such as Japan, pine species are better tsunami forests. Additionally, proper maintenance is required to preserve the forest's mitigation functionality. Trees should be planted with moderate density, and be frequently thinned for appropriate growth control. Otherwise, the trees will not develop to their full size, lessening the effectiveness of their tsunami mitigation role.⁸⁶

⁸⁴ "Effectiveness and Limitations of Vegetation Bioshield in Coast for Tsunami Disaster Mitigation," Norio Tanaka, last modified October 25, 2013, http://cdn.intechopen.com/pdfs/13082/InTech-Effectiveness_and_limitations_of_vegetation_bioshield_in_coast_for_tsunami_disaster_mitigation.pdf

⁸⁵ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

⁸⁶ "Green Belts and Coastal Risk Management," last modified November 11, 2013, http://wbi.worldbank.org/wbi/Data/wbi/wbicms/files/drupal-acquia/wbi/drm_kn2-8.pdf

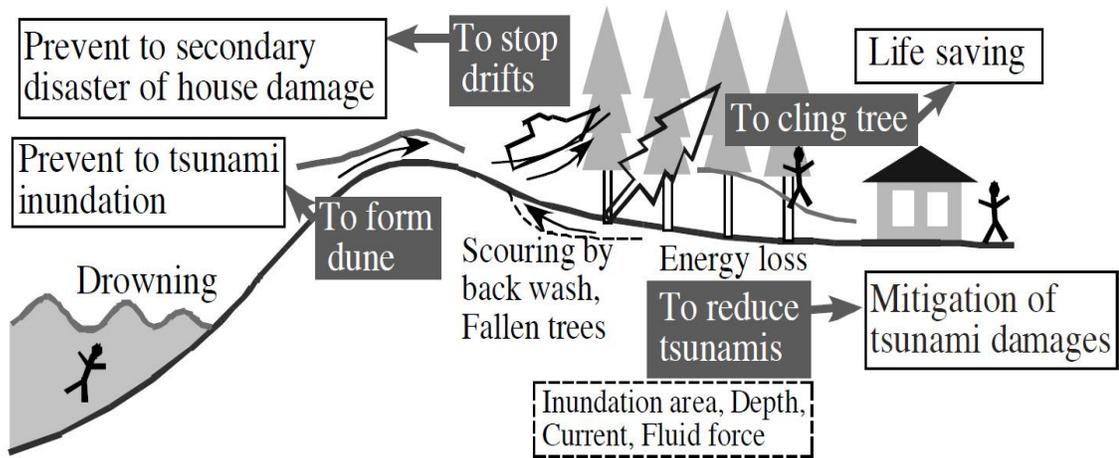


Figure 58: Tsunami Forest functions
 Source: Harada and Imamura⁸⁷

Along Japanese coastlines, forested green belts have been used to mitigate coastal hazards such as sandstorms, salty winds, high tides, and tsunamis for more than four centuries. Even though they are used in several locations, these green belts were seriously damaged in the 2011 tsunami. They still played an important role to reduce the impact of waves, and to protect houses. From the 164,000 hectares of forested green belts around Japan, during the 2011 tsunami 3,660 (ha) were damaged by the tsunami flow. 2,825 ha were flooded, and 1,069 sustained more than 75 percent damage.⁸⁸

⁸⁷ "Effects of Coastal Forest on Tsunami Hazard Mitigation — A Preliminary Investigation," K. Harada and F.Imamura, last modified February 20, 2013. http://link.springer.com/chapter/10.1007%2F1-4020-3331-1_17

⁸⁸ "Green Belts and Coastal Risk Management," last modified November 11, 2013, http://wbi.worldbank.org/wbi/Data/wbi/wbicms/files/drupal-acquia/wbi/drm_kn2-8.pdf

After the 2011 Japan earthquake and tsunami, effectiveness of tsunami forests was measured. The conclusions indicated that the green belt reduced the impact of the tsunami, delayed its arrival time, and protected houses by capturing drifting debris. Past tsunami disasters confirmed the following benefits:⁸⁹

- The energy and speed of tsunami decreased.
- Floating wreckage was blocked.
- People washed away by the tsunami were able to save their lives by clinging to trees.
- The trees helped to preserve sand dunes, which mitigated the force of the tsunami.

iv. Tsunami forest variables involved in tsunami mitigation

A complex equation of parameters plays a role in the tsunami mitigation in many different types of coastal forests. The most relevant parameters are: the forest width, tree density, age, tree diameter and height, and species composition. Each of these parameters can be manipulated to obtain the required level of resistance against the tsunami flow for specific coastal conditions.

Several reports regarding tsunami forests in Southeast Asia, and Japan have shown that tree growth and forest density have a significant effect on tsunami mitigation. This is because trees with larger trunk diameters require more space between them to grow, which involves a lower tree density in the forest. The trunk diameter and forest density need to be discussed together in order to provide enough space for the maximum growth of the trees.⁹⁰

The United Nations Food and Agriculture Organization (FAO) pointed out the necessity of active forest management in order to produce variously aged stands of trees. Trees should be different sizes, as well as have branches at all levels to improve the potential of mitigation, especially in small tsunamis. A variety of tree species may improve the

⁸⁹ "Green Belts and Coastal Risk Management," last modified November 11, 2013, http://wbi.worldbank.org/wbi/Data/wbi/wbicms/files/drupal-acquia/wbi/drm_kn2-8.pdf

⁹⁰ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

mitigation effectiveness of the tsunami forest. Species must tolerate a salty environment, and be able to grow under the shade of the taller trees for smaller species.⁹¹

Forest width is one of the most important factors in tsunami mitigation. Sufficient forest width is necessary to absorb enough of the tsunami energy to reduce flow velocity and depth before exiting the forest. The energy of the waves is progressively dissipated and reduced by drag and friction created by the trunks, branches, and foliage of a tsunami forest. Even when energy levels are high, the width effect remains strong. Narrower tsunami forests have a greater risk of destruction, while wide tsunami forests have less risk of destruction.⁹² The Forest Agency of Japan suggests that the forest should be at least 50 meters wide, and preferably 200 meters, for effective disaster risk management in coastal areas.⁹³

The density in a tsunami forest is defined by the spacing between trees (horizontal density) and the vertical configuration of aboveground roots, stems, branches, and foliage (vertical density). The density in coastal forests is related to the forest's ability to reflect a tsunami, as well as absorb and dissipate its energy. A moderate density is the most effective in tsunami mitigation. If too sparse, tsunami waves will pass through unmitigated. On the other hand, if the forest is too dense, a large wave could pass over unmitigated, or destroy the tree barrier. In the same context, a forest with sparse undergrowth and trees with few branches in the lower levels will provide less mitigation than a forest with high vegetation density from the ground to the canopy.⁹⁴ In general, by increasing the vertical and horizontal density will enhance the mitigation effect of a coastal forest.

⁹¹ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

⁹² "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

⁹³ "Green Belts and Coastal Risk Management," last modified November 11, 2013, http://wbi.worldbank.org/wbi/Data/wbi/wbicms/files/drupal-acquia/wbi/drm_kn2-8.pdf

⁹⁴ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

In most cases, the tree's age and growing conditions define the height and average diameter of the forest. In older forests the diameter and height usually enhance the mitigation effects of the trees. In the same way, diameter growth improves the resistance against breakage of trunks and branches. Inadequate growing conditions will not allow the trees to reach their maximum size, reducing the mitigation capacity of the forest. The taller the forest is, the greater the reflective area of the forest's front, and the lower the potential of being overtopped by a tsunami wave.

The species' growth impacts tsunami forests level of tsunami mitigation. Each tree species has a specific resistance to impact and requires different growing conditions. In order to optimize the mitigation capacity of a coastal forest, a combination of different tree species is recommended. It has been observed that two layers of vegetation in the vertical direction exhibit a strong potential to decrease the damage generated by tsunami flood.⁹⁵ Tree species that retain lower branches can significantly contribute to improved density in lower layers. Changes in species composition resulting from colonization by invasive species can affect the capacity of coastal forests and their mitigation of tsunamis.⁹⁶

v. Limitations and demerits of coastal forests

There exist two main groups of possible mitigation failures in a protective green belt. In the first group are failures related to the natural properties of the trees when they are exposed to tsunami forces. In this group, the most important warning is the risk of complete destruction of the affected forest, as well as the hazard from the debris flow. The second group contains failures associated with forest design and the proximity to the urban environment. In this second group, the main issues are the gaps where the tsunami flow tends to be accelerated, increasing the potential of destruction.

⁹⁵ "Effectiveness and Limitations of Vegetation Bioshield in Coast for Tsunami Disaster Mitigation," Norio Tanaka, last modified October 25, 2013, http://cdn.intechopen.com/pdfs/13082/InTech-Effectiveness_and_limitations_of_vegetation_bioshield_in_coast_for_tsunami_disaster_mitigation.pdf

⁹⁶ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

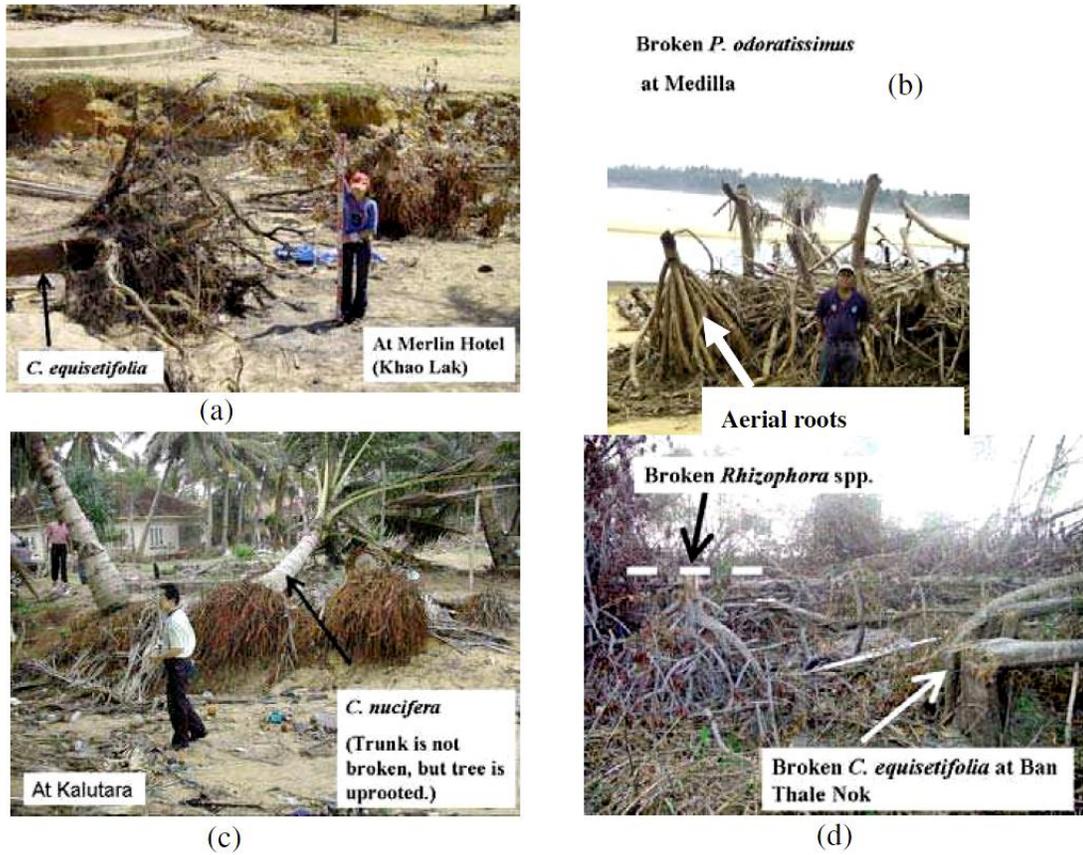


Figure 59: Damaged Tree Patterns: (a) Erosion and overturning, (b) (d) Tree trunk breakage, (c) Uprooted. Source: Tanaka 2011⁹⁷

When a forest has insufficient density, width, soils substrate strength, or tree diameter, the flow of a tsunami is able to uproot trees or break the trees' trunks and branches. When this happens, the broken material becomes debris that can be carried inland by the tsunami. The damage caused by debris-laden water flow can exceed the damage caused by water alone because of the greater mass and inertial forces of the objects carried along with it.⁹⁸ However, many studies have revealed that these failures can be overcome with proper planning and management.

⁹⁷ "Effectiveness and Limitations of Vegetation Bioshield in Coast for Tsunami Disaster Mitigation," Norio Tanaka, last modified October 25, 2013, http://cdn.intechopen.com/pdfs/13082/InTech-Effectiveness_and_limitations_of_vegetation_bioshield_in_coast_for_tsunami_disaster_mitigation.pdf

⁹⁸ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

The cross-sectional area of the trunk and branches of a tree is a major factor determining the horizontal breaking strength. Any increase in the stem diameter will dramatically increase the breaking strength and stability of a tree. The density and structure of the wood are also important in determining the mitigation potential of a forest. The characteristics of breakage resistant species are: rigid and dense, or elastic and forgiving.⁹⁹

A problem associated with forest mitigation, either natural or designed, is the existence of gaps. In most cases, a gap in the coastal forest will increase risks and potential damage. Gaps are found at the mouth of rivers and mangrove channels opening into the sea. Homesteads, beach access, and roads are some urban components that create gaps in coastal vegetation. A tsunami impacting a forest barrier will be funneled through gaps in the landscape.

c. Dune construction and Beach nourishment

Dune construction is the piling up of beach sand to form protective dune fields to replace those washed away during severe storms by wind or flood action. An essential component of dune reconstruction is the planting of dune vegetation and placement of netting or snow fencing to help retain wind-blown sand normally trapped by mature dune vegetation.

Beach nourishment is a soft structure solution used for prevention of shoreline erosion. Material of preferably the same or larger grain size and density as the natural beach material is placed on the eroded part of the beach to compensate for the lack of natural supply of beach material. The beachfill might protect the beach as well as downdrift stretches.¹⁰⁰

⁹⁹ "The role of coastal forests in the mitigation of tsunami impacts," FAO, last modified January 25, 2014, <http://www.fao.org/forestry/14561-9bf06569b748c827ddd4003076c480c.pdf>

¹⁰⁰ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 36.

A key feature of almost every coastal area along the east coast of Japan is a large seawall or barrier built along the coast to protect upland areas from tsunami inundation. While these walls would be effective against large wind waves in severe storms, their primary purpose was to protect against tsunami wave impact. Vertical concrete floodwalls were highly affected by lateral forces produced by the tsunami flood. In most of the cases these walls survived, but with evident damage due to scour.¹⁰²



Figure 61: Seawall Collapse in Fukushima
Source: DailyMail¹⁰³

Successful coastal structures were all those that were not exceeded by the tsunami flood, protecting the population located behind them. For example, the 15 meter high (49 ft) tsunami wall built to protect the community of Otanabe, was 2.5 meters (8 ft) above the run-up elevation, and the structure protected the community from inundation. However, the fishing port was placed on the seaside of the tsunami wall, resulting in total destruction. Even though several tsunami walls along the east coast were exceeded by the

¹⁰² Gary Chock et al., *Tohoku, Japan, Earthquake and Tsunami of 2011 Performance of Structures Under Tsunami Loads* (Reston: American Society of Civil Engineers, 2013), 179.

¹⁰³ "Genesis of a disaster: Moment tsunami swamps Japan's doomed Fukushima nuclear plant," last modified May 20, 2011, <http://www.dailymail.co.uk/news/article-1388629/Japan-tsunami-destroyed-wall-designed-protect-Fukushima-nuclear-plant.html>

tsunami flood's height, most of them helped to reduce the damage to the inland community.

Seawall damage can be comprehensive in scale and generate massive debris that can travel with the inflow. Large sections of tsunami barriers failed over shoreline lengths ranging up to several hundred meters. Failed sections allowed strong tsunami flows both as the tsunami came ashore and the tsunami water receded. Very large segmented concrete seawalls were susceptible to overturning after scouring due to the overtopping flow. Lack of continuity between elements allowed for significant failure.¹⁰⁴



Figure 62: Failed section of Coastal Revetment
Source: ASCE 2011¹⁰⁵

Another type of construction used in numerous tsunami barriers consisted of a trapezoidal compacted-earth cross section surrounded by cast-in-place concrete slab panels. These

¹⁰⁴ Gary Chock et al., *Tohoku, Japan, Earthquake and Tsunami of 2011 Performance of Structures Under Tsunami Loads* (Reston: American Society of Civil Engineers, 2013), 213.

¹⁰⁵ "Japan Earthquake/Tsunami Reconnaissance," ASCE, last modified June 29, 2011, <http://www.asce.org/PPLContent.aspx?id=12884907221>

barriers fared poorly. Common failure mechanisms included the removal of top or rear concrete panels slabs, with subsequent erosion and scour of the compacted earth core. In most cases, it appeared that the tsunami waves severely inundated the structures and that the design was not robust enough against massive overtopping flows.¹⁰⁶ In general the concrete-lined compact-earth barriers were not effective, and many suffered widespread failure.



Figure 63: Collapsed Funakoshi East Breakwater
Source: UNC¹⁰⁷

Many of the coastal structures did not perform well during the tsunami flood. The large range of coastal destruction demonstrates that the shore protection structures did not provide effective protection of inland communities. A limited number of coastal barriers succeeded, most were partially or totally destroyed. Many structures collapsed or slid off

¹⁰⁶ Gary Chock et al., *Tohoku, Japan, Earthquake and Tsunami of 2011 Performance of Structures Under Tsunami Loads* (Reston: American Society of Civil Engineers, 2013), 189.

¹⁰⁷ "Lighthouses of Japan: Iwate," last modified August 29, 2014, <http://www.unc.edu/~rowlett/lighthouse/jphn1.htm>

their foundations. Segments of wall detached from main structures, generating debris, which impacted in the buildings and destroying structural and non-structural components (Figure 64). Furthermore, armor units broke into pieces and revetments scattered.¹⁰⁸ Even though many of the tsunami walls failed to protect inland communities, some wall's structure sections remained in good condition, being able to be incorporated in future community planning.



Figure 64: Debris impact damage in buildings, Natori
Source: ASCE 2011¹⁰⁹

Scour on the landside of structures, and at ends was very common. Although a nuisance in many places, scour in some locations was sufficient enough to damage structures or put them in danger (Figure 65). Foundation failures occurred when tsunami forces pushed

¹⁰⁸ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 64.

¹⁰⁹ "Japan Earthquake/Tsunami Reconnaissance," ASCE, last modified June 29, 2011, <http://www.asce.org/PPLContent.aspx?id=12884906433>

structures off their foundations. Minimal foundation connectors contributed to a number of the failures, and many gravity structures lacked mechanical foundation of any kind.

Greenbelt barriers proved ineffective as protection from tsunami inundation and fast moving currents. The tsunami flood exceeded the protective function of these vegetative barriers. In certain locations, the tsunami ripped out floating projectiles or created localized dams.¹¹⁰



Figure 65: Scour in Sendai's Seawall
Source: ASCE 2011¹¹¹

¹¹⁰ Lesley Ewing, Shigeo Takahashi, and Catherine M. Petroff, *Tohoku, Japan, Earthquake and Tsunami of 2011* (Reston: American Society of Civil Engineers, 2013), 64-68.

¹¹¹ "Japan Earthquake/Tsunami Reconnaissance," ASCE, last modified June 29, 2011, <http://www.asce.org/PPLContent.aspx?id=12884906961>



Figure 66: Overturned tsunami wall, Kohirahama.
Source: ASCE 2011 ¹¹²

¹¹² "Japan Earthquake/Tsunami Reconnaissance," ASCE, last modified June 29, 2011, <http://www.asce.org/PPLContent.aspx?id=12884906959>

2. Sumatra, Indonesia 2004.

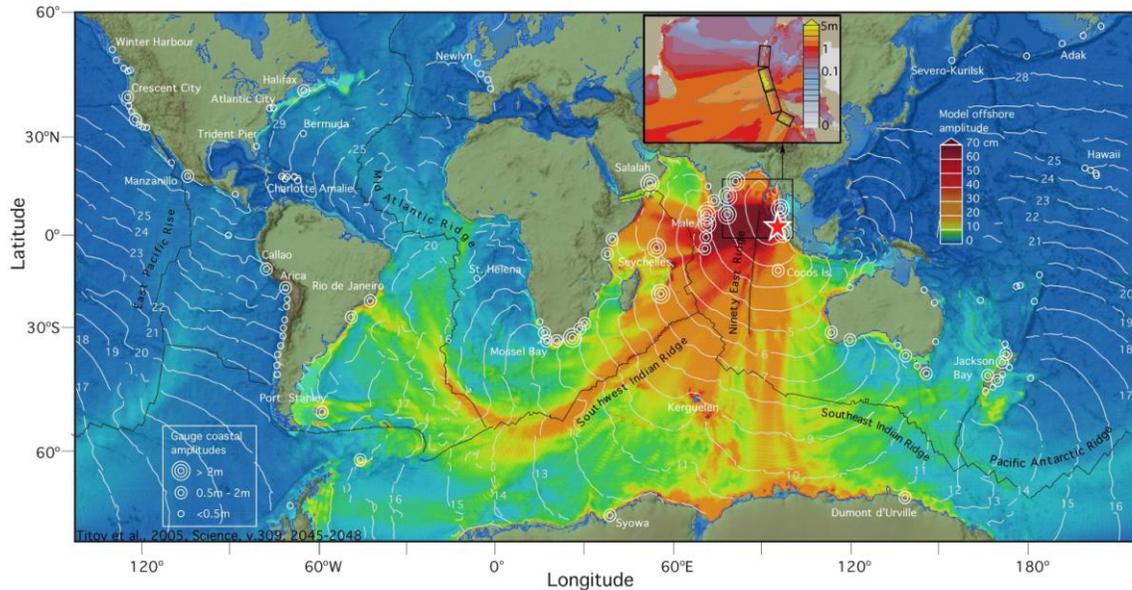


Figure 67: 2004 Sumatra Tsunami propagation

Source: NOAA ¹¹³

After an earthquake of 9.2 Richter, the fault rupture uplifted the ocean floor, releasing the most destructive series of tsunami waves in recorded history in the Indian Ocean, causing damage in the coastal communities of 12 countries. The most damaging effects registered in Aceh Province, where three devastating waves struck the western shore within about 30 minutes. The tsunami waves ranged from 4 to 39 meters high and destroyed more than 250 coastal communities around the Indian Ocean.¹¹⁴

¹¹³ "Tsunami Sumatra," last modified January 10, 2014, <http://www.pmel.noaa.gov/images/headlines/2004-ampmap.jpg>

¹¹⁴ Carl Strand and John Masek, *Sumatra-Andaman Islands Earthquake and Tsunami of December 26, 2004 Lifeline Performance* (Reston: American Society of Civil Engineers, 2008), 3-5.



Figure 68: Failure of a sewage line due to scour
Source: ORWARN ¹¹⁵



Figure 69: Collapsed concrete waterfront due to scour, Chennai
Source: ORWARN ¹¹⁶

¹¹⁵ "Tsunami Damage to Infrastructure," Harry Yeh, last modified January 10, 2014,
http://www.orwarn.org/files/ORWARN%20Tsunami%20Damage%20To%20Infrastructure_HarryDay.pdf

¹¹⁶ "Tsunami Damage to Infrastructure," Harry Yeh, last modified January 10, 2014,
http://www.orwarn.org/files/ORWARN%20Tsunami%20Damage%20To%20Infrastructure_HarryDay.pdf

Residential neighborhoods and fishing villages in coastal areas were completely destroyed, and houses were swept inland or out to sea. The traditional construction that had resisted the earthquake shaking damage could not resist the tsunami forces and most were destroyed. Most well designed and well constructed concrete buildings and industrial facilities that had withstood the earthquake shaking also withstood the tsunami waves and suffered only minor damage.



Figure 70: Concrete building after tsunami flood, Banda Aceh
Source: ORWARN¹¹⁷

Several one- and two-story administrative buildings and machine shops were smashed by waves carrying large, nearly empty, oil-storage tanks. The impact of the waves also caused non-structural damage to some of the buildings. For example, metal siding and

¹¹⁷ "Tsunami Damage to Infrastructure," Harry Yeh, last modified January 10, 2014,
http://www.orwarn.org/files/ORWARN%20Tsunami%20Damage%20To%20Infrastructure_HarryDay.pdf

other non-structural components were stripped from the steel-frame buildings up to the height of the waves.¹¹⁸

The low-lying topography of most of the affected coastal area, as well as the height of the water, resulted in debris being swept in and out by the three successive destructive tsunami waves. This situation generated large, heavy projectiles, such as cars, trucks, and fishing boats, which were swept in and out, each time impacting previously undamaged facilities.

Many small buildings were structurally damaged by tsunami waves carrying floating debris. Partially full storage tanks, bridges, and other light structures that were not anchored to their foundations were not able to resist the tsunami forces. Tectonic subsidence and liquefaction were significant contributors to the devastation weakening and destroying buildings 'foundations as well as other structural components.¹¹⁹



Figure 71: Total devastation in Banda Aceh
Source: ORWARN¹²⁰

¹¹⁸ "Effects of the 2004 Sumatra-Andaman Earthquake and Indian Ocean Tsunami in Aceh Province," National Academy of Engineers, last modified January 10, 2014, <http://www.nae.edu/Publications/Bridge/EngineeringfortheThreatofNaturalDisasters/Effectsofthe2004Sumatra-AndamanEarthquakeandIndianOceanTsunamiinAcehProvince.aspx>

¹¹⁹ Carl Strand and John Masek, *Sumatra-Andaman Islands Earthquake and Tsunami of December 26, 2004 Lifeline Performance* (Reston: American Society of Civil Engineers, 2008), 246-247.

¹²⁰ "Tsunami Damage to Infrastructure," Harry Yeh, last modified January 10, 2014, http://www.orwarn.org/files/ORWARN%20Tsunami%20Damage%20To%20Infrastructure_HarryDay.pdf

Chapter VI: Waterfront Rehabilitation in Pelluhue County.

A. PRES Rehabilitation plan for Pelluhue county, by Government of Chile

After the earthquake and tsunami of 2010, the Chilean government developed several rebuilding plans focused on the rehabilitation of the most affected areas. The Chilean government, in conjunction with local municipal governments, private donations, and various institutions, developed the plans. The goal of these plans was to generate a guide of rehabilitation of the main public urban infrastructure, as well as to improve the security and quality of life in the cities or small towns affected by the destruction from the earthquake and tsunami.

The rehabilitation efforts for Pelluhue County, one of the most affected localities in the central region of Chile, were part of the PRES: Strategic-Sustainable Rebuilding Plan. This plan was developed by a group of professionals from Pelluhue's Municipality, The Ministry of Housing and Urbanism of Chile, and the foundation "A Roof for Chile". The agreement was signed in May 25th, 2010 and the main purpose was to generate a plan to manage the public and private decisions involved in the process of rebuilding of the affected urban infrastructure.¹²¹

The PRES is providing a replicable model of management, which is developed and executed collectively between the different organizations and participating entities. The strategic and sustainable condition proposed for the PRES is focused on transforming Pelluhue County into a zone of specific touristic interest, by supporting the productive activities in the countryside, with those of the coastal area. The traditional productive activities are visualized as a promoter of tourism in the Pelluhue County, helping to support the conventional touristic attractions: landscape and nautical sports.

¹²¹ "PRES Pelluhue, Memoria Explicativa," MINVU Chile, last modified November 25, 2013, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

The three main components of the PRES are the territorial connectivity, the rehabilitation of urban infrastructure, and the mitigation and prevention of future natural disasters taking place in the county.¹²²

1. Territorial connectivity

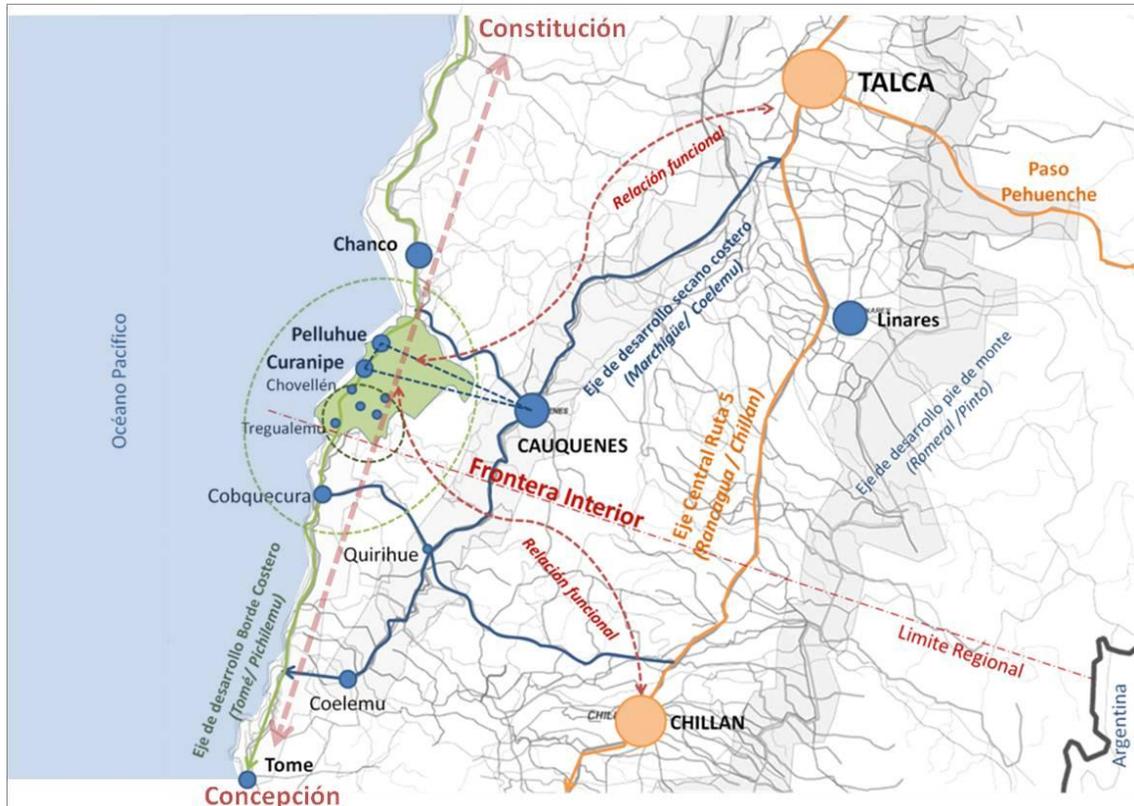


Figure 72: Territorial Strategy PRES
Source: PRES Pelluhue 2010¹²³

¹²² "PRES Pelluhue, Memoria Explicativa," MINVU Chile, last modified November 25, 2013, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

¹²³ "PRES Pelluhue 2010," last modified January 9, 2011, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

The first component in the PRES is to generate connectivity between Pelluhue County and the main urban centers in the region. To develop this connectivity it is necessary to reconstruct the road systems, focusing on connecting Pelluhue County not only with the main supply cities (Talca and Cauquenes), but also with the localities that have a similar origin and demographic but are currently geographically disconnected. In this context, the coastal road is a very important component to rehabilitate, due to the presence of several fishing villages, as well as the two main coastal cities and harbors in the region: Constitucion toward the north, and Concepcion in the south.

Another important component of territorial connectivity is to improve the internal road system. This system is overloaded due to the dramatic increase of population (vacationers) during the summer months. The small streets are not able to deal with the added traffic associated with vacationers and commerce. In this context, the PRES proposes a change to the main roads, in order to allow more vehicular circulation during the summer, and recuperate the conventional road structure during the winter.

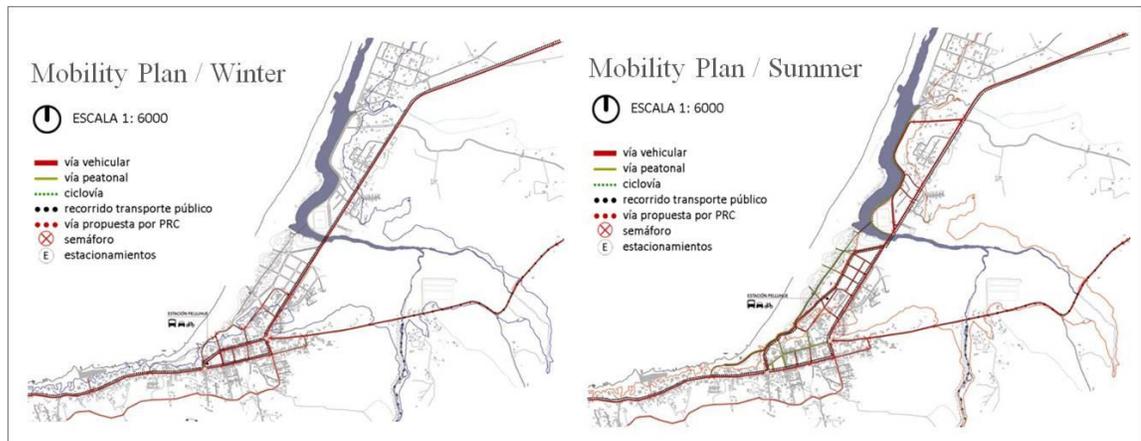


Figure 73: Mobility Plan: Winter and Summer
Source: PRES Pelluhue 2010¹²⁴

¹²⁴ "PRES Pelluhue 2010," last modified January 9, 2011, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

The territorial connectivity creates conditions in Pelluhue that consolidate the county as a productive region, in order to create an auto sustainable region, with less dependence on external supply to operate. The rehabilitation of coastal productive areas and fishing infrastructure is essential to achieve this condition.¹²⁵

2. Rehabilitation of Urban Infrastructure

The set of interventions proposed by the PRES are directly related to the immediate needs after the earthquake and tsunami destruction to recuperate the functionality of buildings and institutions. Initially, these measures were focused on rehabilitation of the public infrastructure to provide the minimal conditions for the normal operations of the county. These procedures involve the repair of the damaged basic utilities, such as drinking water, electricity, and emergency services. The local emergency office coordinated with the central regional government, to meet the needs of the county directly following the catastrophe. These entities were incorporated with the local government of Pelluhue County in order to guarantee the operation of public services and communitarian equipment.

¹²⁵ "PRES Pelluhue, Memoria Explicativa," MINVU Chile, last modified November 25, 2013, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

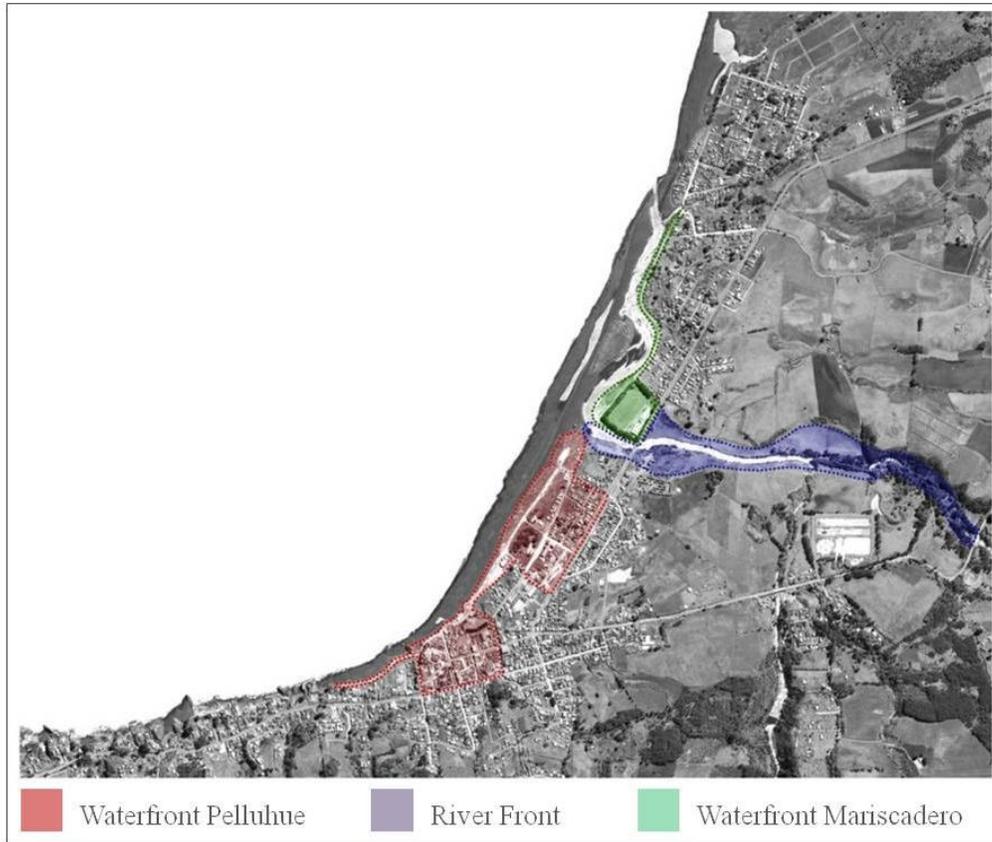


Figure 74: PRES interventions in Pelluhue
Source: Source: PRES Pelluhue 2010 ¹²⁶

The main interventions made to Pelluhue's waterfront were the rehabilitation of the elementary school, shoreline cleanup from tsunami debris, rehabilitation of utilities, and repair to the damaged Curanilahue Bridge, which is the north access to the county. The riverfront of Pelluhue was cleaned and a new artificial canalization to control the flow of water was proposed. A recreational park was proposed to mitigate and reduce the destruction in future events associated with river flood. In Mariscadero's waterfront, one of the most affected areas in the county, the destroyed bridge that connects Mariscadero

¹²⁶ "PRES Pelluhue 2010," last modified January 9, 2011, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

with Pelluhue was replaced. It was also proposed to build an artificial canalization at this location in order to focus on potential flood zones.¹²⁷

3. Mitigation and Prevention of future Natural Disasters

These interventions directly respond to the high degree of destruction experienced in Pelluhue County after the 2010 earthquake and tsunami. The PRES proposed the implementation of small defensive coastal structures (parapet walls) along the urban waterfront in Curanipe and Pelluhue. This wall would prevent erosion in regular conditions as well as conducts water flows during tsunamis or storms along the urbanized areas of Pelluhue County's waterfront (Figure 75).

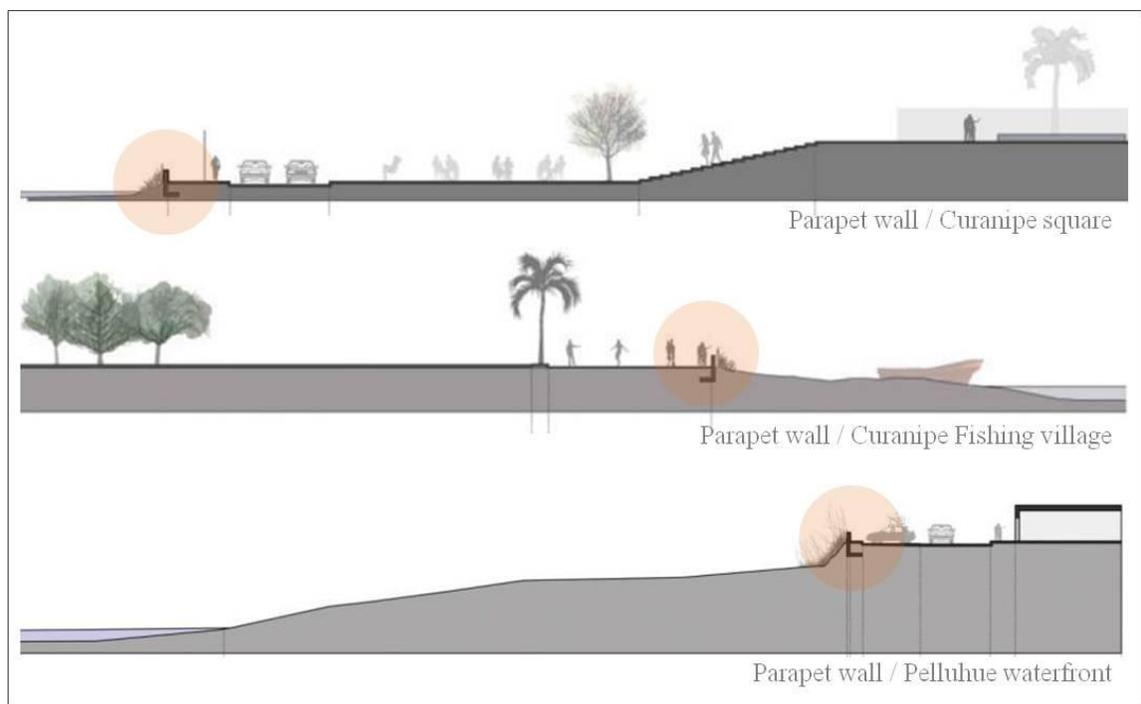


Figure 75: PRES Parapet walls interventions in Pelluhue
Source: Source: PRES Pelluhue 2010¹²⁸

¹²⁷ "PRES Pelluhue, Memoria Explicativa," MINVU Chile, last modified November 25, 2013, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

The PRES also proposed to implement natural defensive barriers to mitigate damages in the waterfront of the main populated areas, as well as the protection of the riverfront. The interventions included: tree barriers, forestation of the most susceptible areas, creating green belts, and consolidation of coastal dunes as a protective natural structure. These interventions are just mentioned in the PRES, without a defined study of species of tree, the process to consolidate the coastal dunes, and an evolution of natural mitigation systems.

¹²⁸ "PRES Pelluhue 2010," last modified January 9, 2011, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>



Figure 76: PRES Natural Mitigation interventions
 Source: Source: PRES Pelluhue 2010 ¹²⁹

¹²⁹ "PRES Pelluhue 2010," last modified January 9, 2011, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

B. Tsunami Mitigation Strategies

Mitigation systems can cover a wide range of interventions, from community planning to specific coastal defensive structures. Most of the defensive strategic measures to mitigate damages were reanalyzed after the tsunami of Japan in 2011. The coastal mitigation systems that have been developed through time have been based on scenarios of tsunamis that have occurred with a relative frequency and predictable height. Those systems have achieved the protection of coastal population with varying degrees of success. However, the tsunami height reached in Japan's 2011 disaster considerably exceeded the tsunami height that these defensive structures were designed to mitigate. Some of these structures were effective in reducing the water levels, delaying the arrival of the tsunami waves, and maintaining the coastline. However, most of the coastal protection facilities and coastal structures were damaged and the land behind these facilities suffered significant damage.

Raising the potential tsunami height for coastal protection structures is not realistic from the position of financial demand, quality of life of coastal inhabitants, and the natural environment. These coastal protection facilities, and coastal defensive structures, must continue to be constructed for the frequent tsunamis with a known level of tsunami height from the point of view of protecting human life and the assets of residents, stabilizing the regional economy, and securing efficient industrial bases.¹³⁰

The most commonly used strategies for mitigation of tsunami damages include land use management, planting and environmental preservation, structural designs, hazard awareness, and early tsunami warning. Land use management deals with the placement of buildings in at-risk areas. It suggests that for most of the cases of coastline affected by tsunamis, all the buildings should be built 2 to 3 meters above the level of the higher

¹³⁰ "Damage due to the 2011 Tohoku Earthquake and Tsunami and its lessons for future mitigation," Fumihiko Imamura and Suppasr Anawat, last modified November 25, 2013. <http://www.jaee.gr.jp/event/seminar2012/eqsympo/pdf/papers/118.pdf>

locally registered tsunami record, and public buildings placed 400 meters from the coast.¹³¹

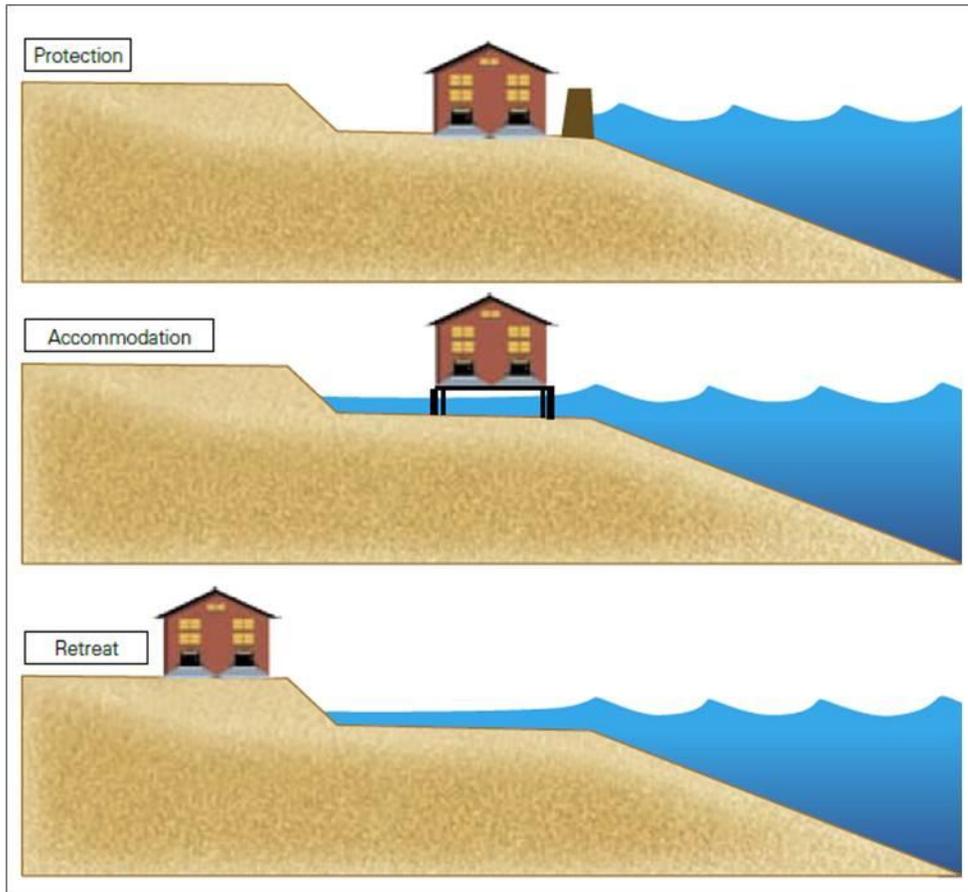


Figure 77: The three mitigation strategies: protection, accommodation and retreat.
Source: ICAM 2009¹³²

Risk mitigation strategies can be classified into three main types: protection, accommodation, and retreat. Policy makers will often implement a combination of these measures for an effective and practical response. These strategies include both structural

¹³¹ "How to Save a Life: Tsunami Mitigation Strategies," Accessed October 25, 2013, <http://geol105naturalhazards.voices.wooster.edu/how-to-save-a-life-tsunami-mitigation-strategies/>

¹³² "Hazard Awareness and Risk Mitigation," last modified January 12, 2009, <http://www.ehs.unu.edu/file/get/5687>

and nonstructural measures. Structural measures refer to any physical (natural or artificial) construction to reduce or avoid possible impacts of hazards.

Structural measures can range from engineered structures to protect development, to buildings designed to better withstand coastal hazard impacts. Non-structural measures refer to policies, regulations and plans that promote good coastal management practices to minimize risks from coastal hazards.¹³³

The destructive impact experienced in Chile 2010, and Japan 2011 tsunamis, reveal current problems with disaster management measures that depended too heavily on coastal protection facilities.¹³⁴ It is essential that tsunami countermeasures be developed for the largest registered tsunamis flood heights. It is also necessary to maintain a minimal reliance on social and economic functions such as local governmental functions, emergency entities, and hospitals. For this, it is necessary to propose comprehensive tsunami countermeasures embracing every possible mechanism, which places evacuation at the core and combines land use planning, evacuation facilities, and disaster management facilities for ultimate protection.¹³⁵

1. Incorporating Tsunami Mitigation strategies in Pelluhue County

Due to the dynamic condition of shorelines, tsunami mitigation measures in Pelluhue County should not be developed in isolation. It is important to understand the natural hydraulic behavior of the coastline, including the sediment transport regime, which controls the stability of the coastal shore. It is important to ensure that mitigation that

¹³³ "Hazard Awareness and Risk Mitigation," last modified January 12, 2009, <http://www.ehs.unu.edu/file/get/5687>

¹³⁴ "Damage due to the 2011 Tohoku Earthquake and Tsunami and its lessons for future mitigation," Fumihiko Imamura and Suppasr Anawat, last modified November 25, 2013. <http://www.jaee.gr.jp/event/seminar2012/eqsympo/pdf/papers/118.pdf>

¹³⁵ "Damage due to the 2011 Tohoku Earthquake and Tsunami and its lessons for future mitigation," Fumihiko Imamura and Suppasr Anawat, last modified November 25, 2013. <http://www.jaee.gr.jp/event/seminar2012/eqsympo/pdf/papers/118.pdf>

works at one coastal location does not lead to instability in adjacent shore locations. Structural protection may be achieved by coastal engineering design such as offshore breakwaters, dikes and revetments, but also by incorporating natural mitigation methods, taking advantage of the complete potential of coastal ecosystems, which can include coastal vegetation and sand dunes.¹³⁶

The natural solutions can provide low cost, as well as environmentally friendly solutions to mitigate tsunami risks. The typology of the protection systems employed should also be effective to mitigate other physical hazards, such as storm surges and extreme wind-forced waves. At the same time, natural mitigation measures can support and generate more diversity of natural microenvironments in the coastal zone. In Pelluhue County, the incorporation of natural mitigation systems might be achieved by incorporating single measures or hybrid solutions, such as combinations of artificial methods or a combination of natural and artificial methods as suggested by PRES.¹³⁷

¹³⁶ Intergovernmental Oceanographic Commission of UNESCO. 2011. Reducing and managing the risk of tsunamis , accessed November 25, 2013. <http://unesdoc.unesco.org/images/0021/002147/214734e.pdf>

¹³⁷ "PRES Pelluhue 2010," last modified January 9, 2011, <http://www.slideshare.net/rmorisuc/pres-pelluhue-20101118-def>

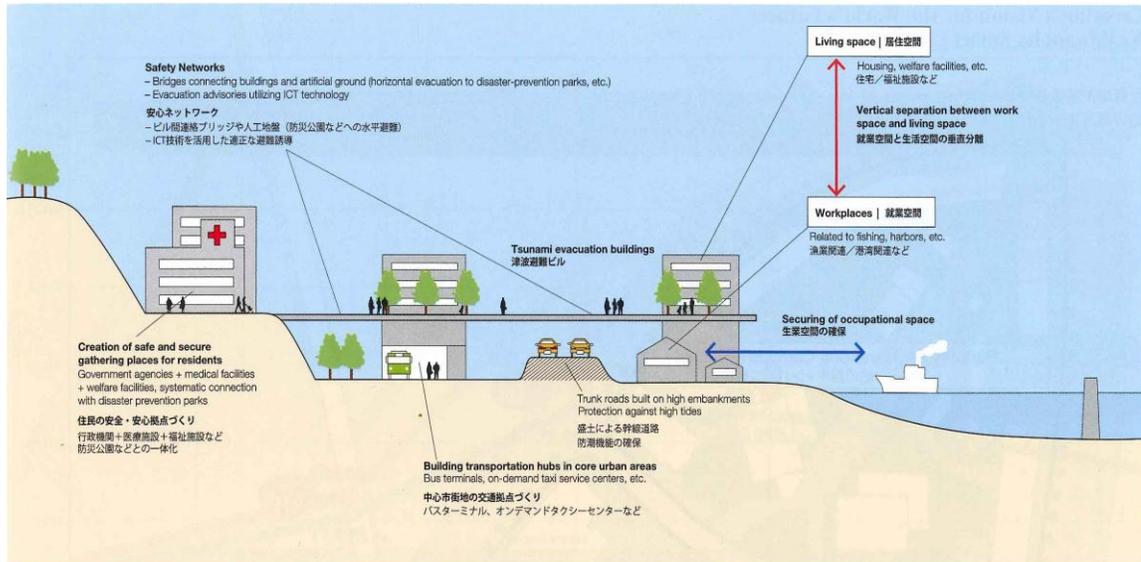


Figure 78: BuildNet Work City / Strategic Tsunami Mitigation
Source: a+u magazine¹³⁸

In 2011 the Intergovernmental Oceanographic Commission of UNESCO developed a guide to reduce and manage the risks associated with tsunamis. This guide provides three measures, which prevent catastrophic damage from the impact of a tsunami. The first measure is a partial barrier, located in the near shore zone, to reduce the impacts of tsunamis before they reach the shoreline. These structures are usually offshore breakwaters that dissipate part of the incoming tsunami's energy before its waves reach the shore. A second measure is a full barrier at the shoreline, to prevent the inundation of tsunamis. The third strategy consists of a partial barrier at the shoreline to reduce the impact of tsunamis crossing the shoreline. These three measures are possible to implement in the affected urban coastal zones of Pelluhue County.¹³⁹

Full and partial barriers (artificial or natural), are physical interventions which may be considered as a protective solution for populated coasts. When designing artificial

¹³⁸ Yoshida, Nobuyuki, and Kabushiki Kaisha Sekkei, "Face to face with nature: cities, architecture, people," A+U, August 2012.

¹³⁹ Intergovernmental Oceanographic Commission of UNESCO. 2011. Reducing and managing the risk of tsunamis , 30 accessed November 25, 2013. <http://unesdoc.unesco.org/images/0021/002147/214734e.pdf>

barriers, it is necessary to ensure the continuity of sustaining multiple uses of the existing natural environment so the beach is not affected by natural disasters or big storms. Full barriers against tsunami inundation may be provided by high-rise seawalls (sea dikes) constructed on the shoreline at or above the high water mark. Where river mouths interrupt the shoreline, tsunami gates can be installed within seawalls to allow for normal flows and traffic access. Sand dunes can provide natural full barriers against tsunami inundation.¹⁴⁰

In Pelluhue, it is essential to define the degree of intervention for each affected area. In the areas where there were no defensive structures, the real necessity of protection must be evaluated. Prior to placing large-scale coastal structures, it is necessary to identify vulnerable groups and areas where the potential for destruction is greatest. At the same time is necessary to reinforce the evacuation routes, and educate the population about safe areas. The integration of interdisciplinary health science, social science, civil engineering, architecture, and urban planning is required to support the continuity of the plan.¹⁴¹

C. Pelluhue's Waterfront Potentialities

In the coastal towns affected by the 2010 tsunami, the waterfront holds the economic, touristic, and recreational activities that support the life of the residents.

The loss of lives, destruction of buildings, as well as the public infrastructure, show the fragility of the coastal areas, and project the occurrence of future natural disasters that could negatively impact the same area. Through the experience of disaster, the coastal communities become aware of the risks associated with placement of the built

¹⁴⁰ Intergovernmental Oceanographic Commission of UNESCO. 2011. Reducing and managing the risk of tsunamis , 30 accessed November 25, 2013. <http://unesdoc.unesco.org/images/0021/002147/214734e.pdf>

¹⁴¹ "Damage due to the 2011 Tohoku Earthquake and Tsunami and its lessons for future mitigation," Fumihiko Imamura and Suppasr Anawat, last modified November 25, 2013. <http://www.jaee.gr.jp/event/seminar2012/eqsympo/pdf/papers/118.pdf>

environment. Through this understanding, there is a desire to incorporate mitigation measures in order to protect the population not only from tsunamis, but also from storms coming from the South Pacific Ocean.

Similarly, Pelluhue's waterfront can now be seen as an area with a high degree of urban potential. It is able to support a sustainable model of development, due to the great availability of natural resources in the county. In the following section, a description of the four main aspects of the waterfront's potentiality will be provided.

1. Productive Waterfront

The majority of the traditional occupations in Pelluhue County are associated with the use of the waterfront area. The initial occupancy of the coastal area was conditioned by the utilization of the coastal resources, as well as the ability to take advantage of the beautiful landscape offered by the sea. Throughout the centuries, different productive activities have taken place in the coastal area, attracting more people to work and live in the coastal area. Today the fishing villages placed in the coastal area represent the main source of food in the county. Most of them are located directly in the zones most affected by tsunami's destruction.

The artisanal fishing involves a set of activities linked with the use of the waterfront area, which are conditioned by seasonal restrictions. When there are no restrictions, the fishing and the associated fishing activities demand a large labor force. Historically, the fishing activities that took place along the coast have strong ties to family life, since most of them have been practiced by a familial group of children and adults alike. This tradition continues to present day.

If practiced in a respectful manner, fishing and seafood production activities add to the overall sustainable development of Pelluhue's waterfront. Since fishing is developed in an artisanal way (not industrial), it has a low ecological impact. In this way, artisanal fishing contributes to the protection of natural resources. At the same time the use of the

waterfront by the local people allows them to warn others about the misuses of the coastal area, especially those made by big fishing industries.

Today, in Pelluhue County, there is a great lack of coastal facilities. The changes in the local geography make Pelluhue's fishing facilities inoperable, displacing them to Curanipe. In order to support the fishing and associated coastal activities, it is essential to construct new infrastructure. The creation of coastal facilities such as a small fishing pier, could also provide future coastal connectivity with other towns in the region, offering a possible supply path if terrestrial roads become inoperable due to natural disasters. Together with improvements made to the connective path and reduced times of operation, the new facilities can contribute to improved security to the fishing activities.

2. Protective Waterfront

Coastal communities are located in strategic locations to reduce the impact of natural catastrophes and storms. At the same time these strategic locations allow the coastal communities to maintain the proximity with the place of work and the sources of food. After the 2010 earthquake and tsunami, the high degree of exposure and vulnerability to tsunami flood was evident in most of the coastal towns in Pelluhue County. The lack of mitigation measures to protect the coastal communities increased the degree of destruction of the urban infrastructure and dwellings during the tsunami. The few existing mitigation elements meant to protect the fishing villages in Curanipe and Pelluhue were not effective, and did not contribute to the protection of the urbanized waterfront.

From this perspective, the waterfront must be understood as a defensive barrier for coastal towns. By incorporating a sustainable mitigation plan in the waterfront area, which incorporates natural measures together with defensive coastal structures, it is possible to protect the population and reduce the destruction during strong storms and tsunami floods. In this way the waterfront is functional and defensive. This waterfront may consider low impact interventions such as incorporation of natural defensive

strategies. At the same time the protective coastal structures may be planned as low ecological impact, and maintain the coastal landscape's natural atmosphere.

3. Recreational Waterfront

Most of the coastal cities around the world have developed a successful model of development based on the recreational potential of the coastal zone. In some locations the natural attractions such as beaches, coastal forests, and reef barriers are featured. In other locations the strategy for creating a coastal attraction has been to place an important building near the waterfront, which complements the coastal landscape and offers services and entertainment to the residents and tourists.

In Pelluhue County only some small-scale touristic private buildings exist, which have been placed next to the coastal area, but without any integration of the public spaces into the projects. These buildings are mostly small cabins and restaurants located in front of the popular beaches. Even though these buildings don't have a negative impact in the landscape, most of the buildings don't promote the integration of the city with the waterfront.

The natural beauty of the landscape, as well as the advantageous sea conditions, has attracted the attention of outdoors athletes, who, depending of the season, find excellent conditions to surf, hike, mountain bike, and sport fish. The good conditions for surfing throughout the whole year have encouraged the development of tourist services, which contribute to sustaining the local economy. Several hostels, focused on accommodating surfers, as well as restaurants and tourist services next to the surf zones have been created. Due to this influx, several surfing championships have been established. These events have successfully caught the attention of surfers and sportsmen worldwide. The natural attractions in the interior of the county complement those on the coastal side, providing a wide range of recreational activities in the county. A sustainable touristic industry could consolidate a recreational waterfront in Pelluhue, and provide natural components to the landscape.

4. Historic-Educational Waterfront

Since most of the activities that have led to the consolidation of Pelluhue County have taken place in the coastal area, the waterfront has a high educational value, which can strengthen the future development of the Pelluhue's waterfront. However, beyond the fishing activities, the waterfront has an educative role that has been developed by the schools to teach the younger generations the great potential and risks associated with sea life. The waterfront also has a wide diversity of endemic species together with a rich variety of seafood and fish. This creates a unique coastal ecosystem, which is an ideal environment to educate the new generations about the utilization and protection of plants and seafood, and the interconnected natural environment.

Pelluhue's waterfront could be used to educate the tourist and the local population about the historic coastal occupations in the town. From the current fishing and seafood production activities, to those activities that are no longer practiced such as: builder and crew of medium-sized wooden vessels called Falucho, which were built with local resources and moved mostly toward Peruvian ports, until the mid 20th century. This traditional occupation was developed and passed down from generation to generation in the same way that artisanal fishing is developed today. However, the development of modern steel shipyards in the south of Chile made this occupation impractical, ending the artisanal boat industry in Pelluhue County. Due to the lack of preservation entities in the region, there is no record of the construction process, plans, or even graphic documentation, which represents a great loss of local heritage.



Figure 79: Construction of a *Falucho* in Curanipe
Source: Picasa¹⁴²

Pelluhue's waterfront also offers an exceptional opportunity to educate the local population and tourists about tsunamis. By showing the watermarks and affected geography, it is possible to make the people aware of the natural disasters that took place in the coastal area. Pelluhue's destroyed coastline was an open tsunami museum right after the 2010 tsunami, where researchers from Chile, and worldwide convened to learn about tsunami effects and destruction. The changes to the geography as well as the destruction can still be seen today.

Since the warning signs of a tsunami take place in the coastal area (sea retreat and wave noise), the waterfront should incorporate an educational program to instruct people about how recognize these signs. To complement this opportunity, the building evacuation routes, connecting the waterfront with the safe areas in the hills, can be highlighted. In this way, the awareness of the dangers will be heightened ensuring the preservation of the waterfront.

¹⁴² "Contrucción de faluchos en el puerto de Curanipe, comuna de Pelluhue," last modified January 12, 2014, <https://picasaweb.google.com/lh/photo/58alEvwTm2P1xZh7761utA>

Chapter VII: Design Exploration for Pelluhue's Waterfront.

Pelluhue town is one of the towns in the center-south region of Chile most affected by the 8.8Mw earthquake and tsunami of 2010. The tsunami flood reached 14m high in populated locations. Most of the damage was localized in the north area of Pelluhue, between the Curanilahue River and the hills of Pelluhue.



Figure 80: Pelluhue town in 2009 and 2010
Source: Flickr 2010¹⁴³

¹⁴³ "Chile, Pelluhue - Antes y después del Tsunami o Maremoto 2010," last modified January 28, 2014, <http://www.flickr.com/photos/28857659@N04/4451941621>

The main reasons for the significant destruction experienced in Pelluhue are the proximity of the urban areas to the coastline and river, as well as the lack of structures (natural or man-made) to mitigate tsunami floods. Most of the buildings were not rebuilt because of the destruction was too great. Four years after the 2010 tsunami, no mitigation work has been built in Pelluhue town. For this reason, several commercial, residential, and municipal buildings in the flood area still illustrate the destruction experienced during the 2010 tsunami.



Figure 81: Pelluhue town affected coastal front.
Source: Felipe Iguait 2014

A. Natural Mitigation Strategies

1. Tsunami Forest intervention in Pelluhue town.

In Pelluhue town, the mitigation work should take advantage of the natural resources available: the natural landscape and good weather conditions. Incorporating a tsunami forest in the coast of Pelluhue, could significantly help to improve the degree of protection to buildings and residential areas that remain exposed today. Additionally, the incorporation of a coastal forest could mitigate the regular coastal storms, control the salt spread by predominant winds, and support the stabilization of the coastal dunes. Coastal dunes significantly reinforce the natural coastal tsunami barrier.

The ideal location for this defensive green belt is the coastal area in front of the most affected urban zone: the area in front of Pelluhue beach and the south side of the Curanilahue River. In this area are beneficial conditions for tree growth. There is also enough surface area available to build a forest with the required dimensions to be highly resistant to tsunami forces.

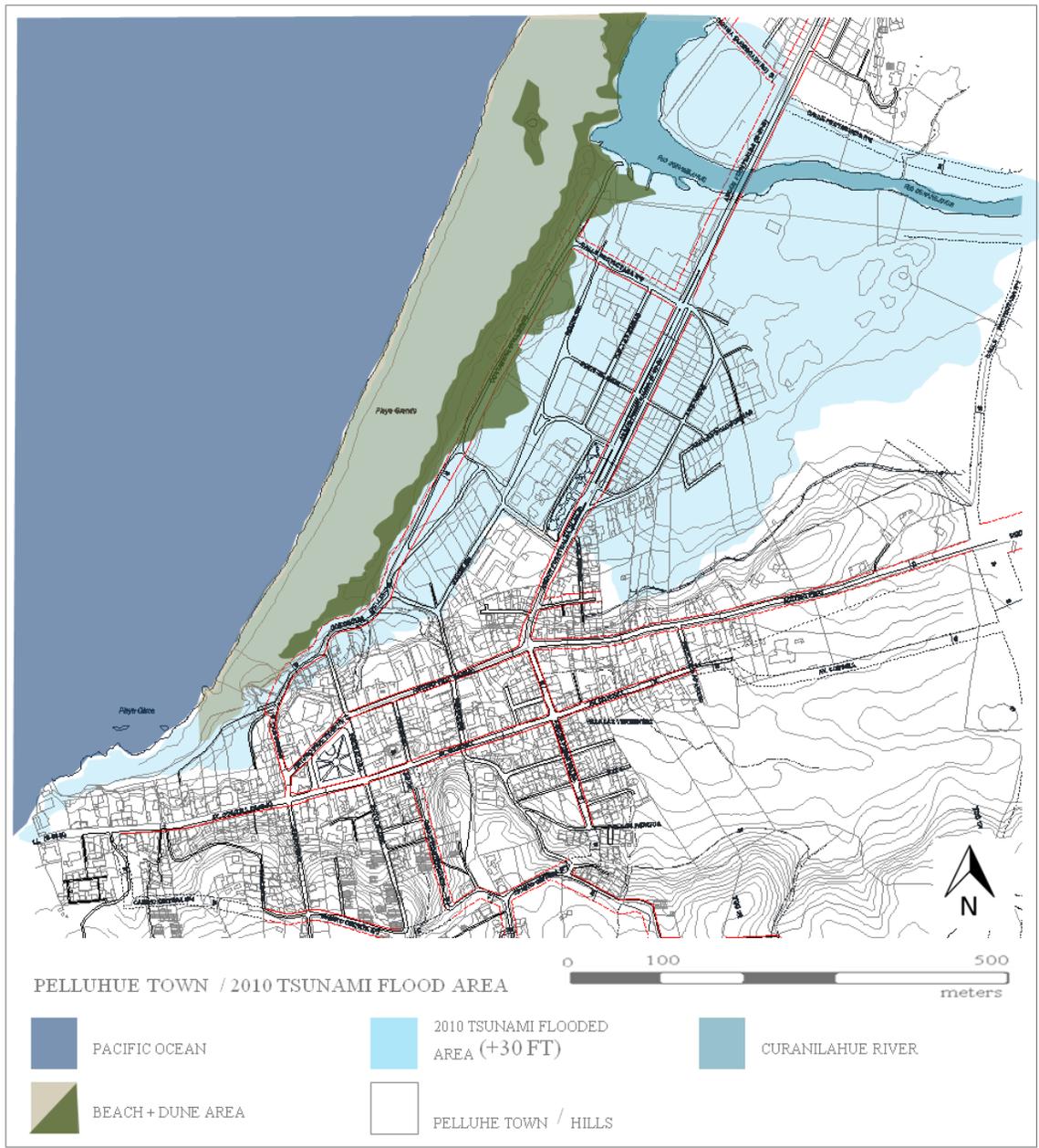


Figure 82: Pelluhue town Flooded Area (2010 Tsunami)
 Source: Felipe Igualt 2014.

The coastal forest in Pelluhue must consider two different waterfronts. One is the coastal front, which is 750 meters (820 yards) long. The other is the riverfront with an extension of 600 meters (656 yards) in length. Most of the area proposed for this tsunami forest was flooded during the 2010 tsunami, or is in the flood warning area.



Figure 83: Pelluhue Coastal Forest Intervention
Source: Felipe Igualt 2014.



Figure 84: Pelluhue Tsunami Forest Intervention / Coastal Front
 Source: Felipe Igualt 2014.



Figure 85: Pelluhue Tsunami Forest Intervention / River Front
 Source: Felipe Igualt 2014.



Figure 86: Pelluhue Tsunami Forest Visualization
Source: Felipe Iguait 2014.

The forest proposed herein has an average width of 100 meters, with a maximum width of 200 meters in the northern corner where the river meets the sea. The minimum width of 60 meters (65 yards) is in the south side of the forest, where the hills raise the land elevation above the flood height. This proposed tsunami forest in Pelluhue satisfies the recommendations from the Forest Agency of Japan, which suggests that the forest should be at least 50 meters wide, and preferably 200 meters, for effective disaster risk management in coastal areas.¹⁴⁴

¹⁴⁴ "Green Belts and Coastal Risk Management," last modified November 11, 2013, http://wbi.worldbank.org/wbi/Data/wbi/wbicms/files/drupal-acquia/wbi/drm_kn2-8.pdf



Figure 87: Pelluhue Tsunami Forest + Dune Barrier Visualization
Source: Felipe Iguait 2014

The proposed tsunami forest covers an area of 28 hectares (69.18 acres) with specific tree species and plants. In front of the tsunami forest is an additional area of 3.7 hectares (9.25 acres) of dunes. This area should be increased to consolidate the sand barrier in front of the forest as well as to encourage the growth of dune plants.

a. Tsunami Forest species selection

The tree species selected for Pelluhue's tsunami forest are: *Pinus radiata*, *Populus alba*, and *Cupresus sempervirens*. This last specie has a strong adaptability to Pelluhue's coastal zone and had a good resistance against the tsunami flood forces during the 2010 tsunami. Additional species could be also incorporated into this tsunami forest, especially smaller trees to provide more opportunities for friction on the forest floor. One possibility is *Acacia melanoxylon*, which has extraordinary adaptability to the Pelluhue coastal area, and develops a strong root system.

A local arborist, considering the micro soil conditions, as well as the possibility to introduce species endemic to the area, should help define these species. The growth of specific undergrowth plants and grass in the dune area should be promoted, especially *carpobrotus aequilaterus* and *lupinus arboreus*, which have an extraordinary adaptability to Pelluhue's coastal weather conditions.

Since the tsunami forest is built by using living materials such as trees and plants, the growing conditions influence the size and density of the proposed forest.¹⁴⁵ This proposed tsunami forest is located in an area with very good conditions to grow trees, as evidenced by surrounding areas of forestry lands. The good soil conditions, as well as the availability of fresh water, predict optimum growth conditions. Additional soil, climate, and water data could be analyzed to increase the advantageous conditions to grow this forest.¹⁴⁶

¹⁴⁵ "Georgia Forest Landowner's Manual," last modified Sept30, 2014, <http://warnell.forestry.uga.edu/SERVICE/LIBRARY/index.php3?docID=47&docHistory%5B%5D=6&docHistory%5B%5D=24>

¹⁴⁶ Jose Alvarez et al., "Factors influencing the growth of radiata pine plantations in Chile," *Forestry Journal* 0.1-14(2012): Accessed October 2, 2014, doi:10.1093/forestry/cps072



Figure 88: Pelluhue Tsunami Forest Tree Species
Source: Felipe Igualt 2014

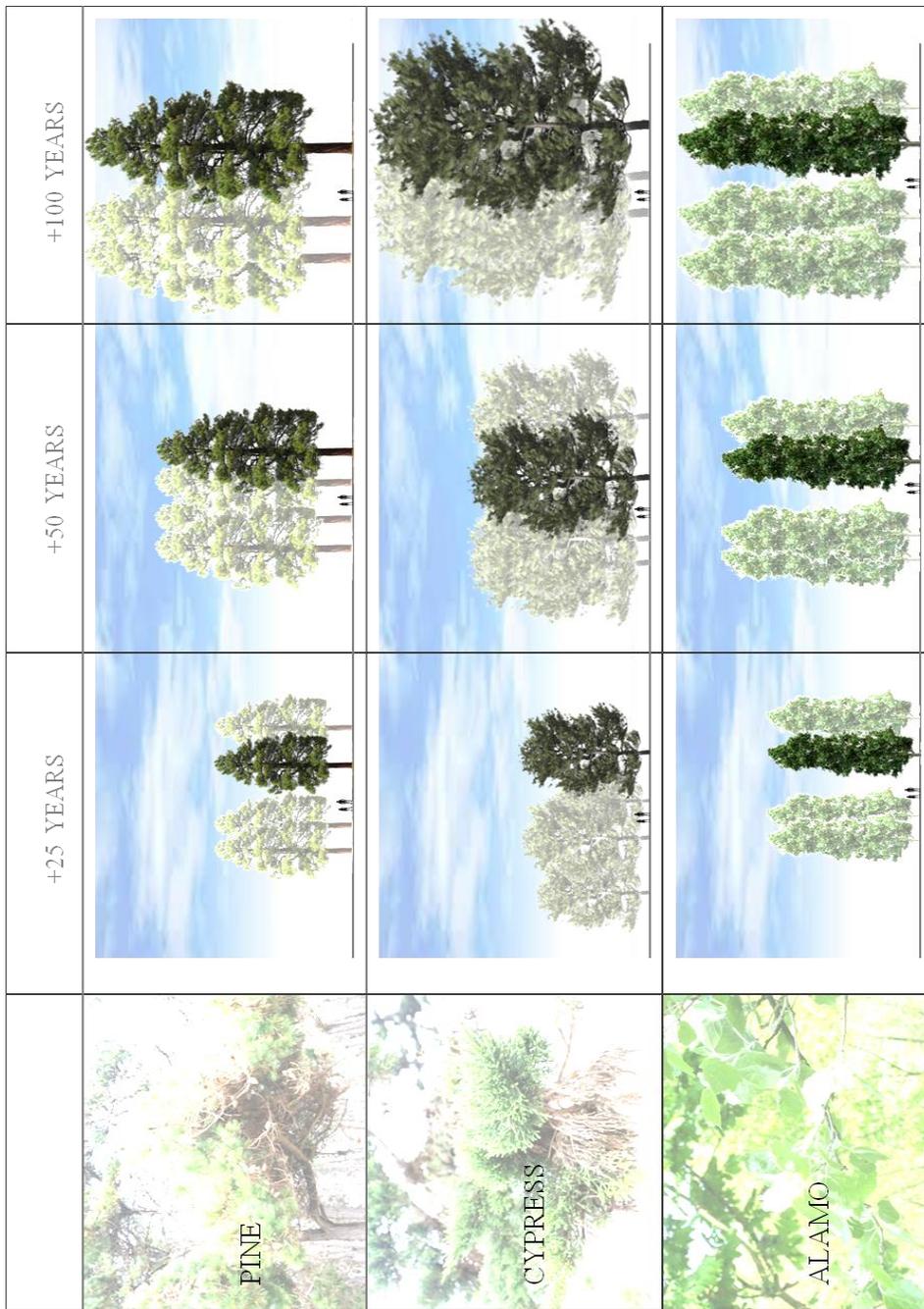


Figure 89: Projected Tree Growth
 Source: Felipe Igualt 2014 + Forestry Journal¹⁴⁷ + Georgia Forest Landowner's Manual¹⁴⁸

¹⁴⁷ Jose Alvarez et al., "Factors influencing the growth of *radiata pine* plantations in Chile," Forestry Journal 0.1-14(2012): Accessed October 2, 2014, doi:10.1093/forestry/cps072

¹⁴⁸ "Georgia Forest Landowner's Manual," last modified Sept30, 2014, <http://warnell.forestry.uga.edu/SERVICE/LIBRARY/index.php3?docID=47&docHistory%5B%5D=6&docHistory%5B%5D=24>

b. Management

The management of the tsunami forest is one of the most important components in the success of this defensive forest. To allow for responsible protection of the forest during the growing process, and the continued maintenance, this defensive green belt should be incorporated into the Chilean national park system CONAF. In this way, the area can be protected by the national forestry corporation, allowing for the correct growing of the different species (dunes + forest + riparian vegetation), and promoting the consolidation of a natural ecosystem around the tsunami forest, and its appropriate maintenance. Successful tsunami forests depend mainly on continuous maintenance.

At the same time that the coastal forest provides a defensive function, the community can take advantage of the new landscape created in the coastal area. From this point of view, the Pelluhue tsunami forest could support the tourism industry, which is the main source of income during the summer season. This coastal forest, in particular, provides facilities for recreation, an area for vegetable production, and camping areas. These productive activities could contribute to support the local economy, generating income for the population and the local government. This income generation will help to support the maintenance costs of the forest.

Gaps in the tsunami forest, such as pedestrian beach access or access roads, must be avoided, due to the destructive effects that gaps produce during tsunami floods. Since they are located in the floodable areas, tsunami forests are not safe areas during tsunami. For this reason, the tsunami forest must be connected to the rest of the town to provide an easy access to the evacuation routes and the safe areas.

2. Coastal Dune barrier

In Pelluhue town there is a natural dune barrier, located just above the beach. This dune barrier parallels the shoreline, reaching an average elevation of 6 meters (20 ft) above sea level. The dunes are interrupted where the Curalinahue River touches the sea. Just in front of Pelluhue town, the dune area covers a surface area of 3.7 Hectares (9.25 Acres). This dune barrier can reach a peak of 10 meters (33 ft) above sea level, depending on erosion by water and wind. The average existing width of Pelluhue's dune barrier is 30 meters (98 ft).

Pelluhue's dune barrier has also been interrupted to create public road to access to the beach. Several interventions, such as landscape equipment implementation and a tsunami memorial sculpture, have been located within the dune field. Strong currents and sea storms have destroyed most of the interventions made after the 2010 tsunami.



Figure 90: Pelluhue town Dune Barrier
Source: Felipe Iguait 2013

By dissipating wave energy, coastal dune barriers can contribute significantly to the mitigation of tsunami floods. Dune barriers also contribute to the structural integrity of the sand bank when strong storms erode the sand beaches. Sand dunes also provide a valuable coastal habitat for many plants and animals, as well as a natural environment for recreation and ecology.

The intervention proposed for Pelluhue's dune barrier, consists initially of supporting the growth and consolidation of the existing dune barrier, by increasing the volume and height of the dunes. The dune barrier, with the proposed tsunami forest, can contribute significantly to mitigate future tsunami flooding, and prevent destruction similar to the 2010 tsunami.

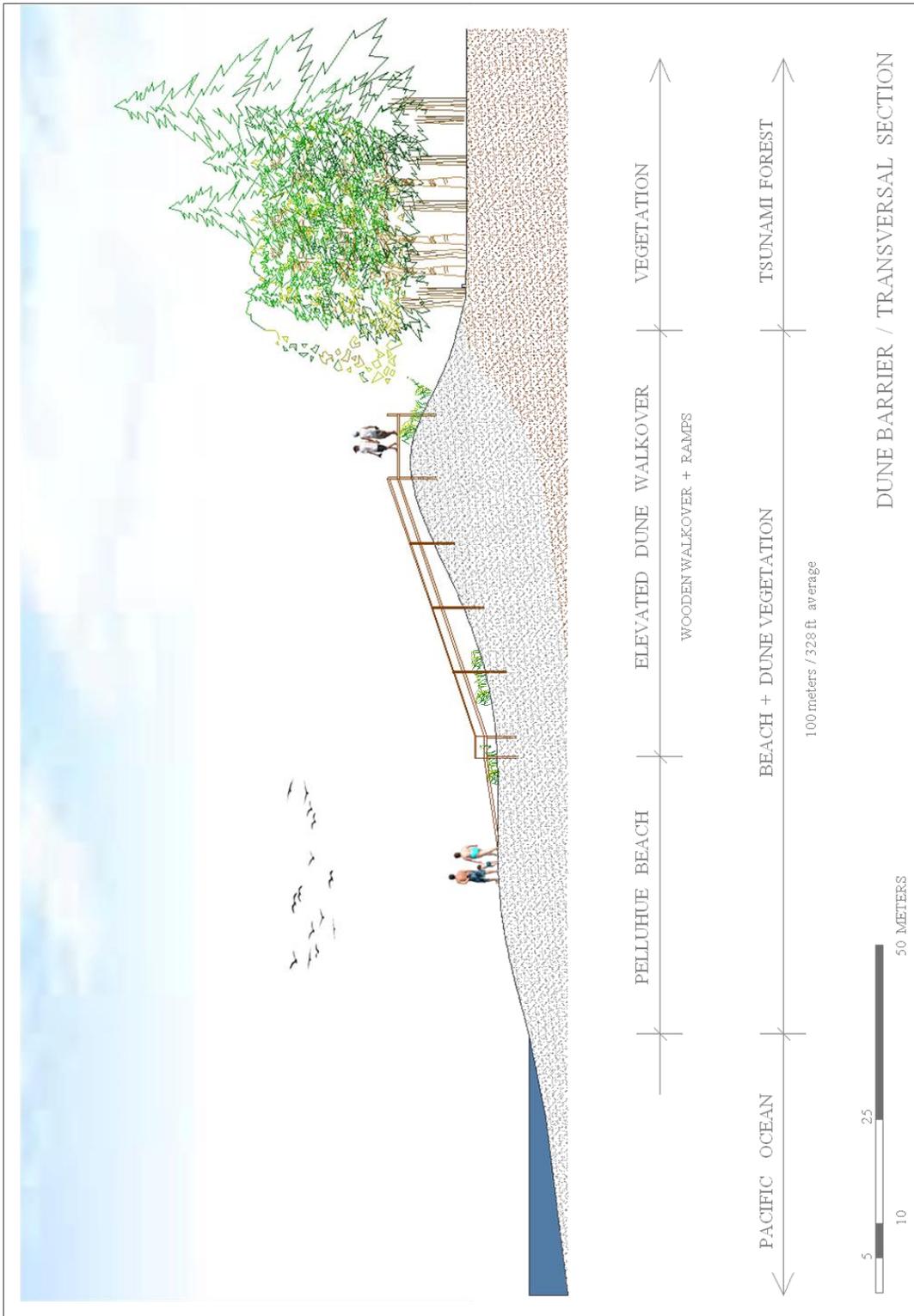


Figure 91: Dune Barrier / Transversal Section
 Source: Felipe Igualt 2014

a. Dune Barrier Species Selection

Many plant species will grow in Pelluhue's dune barrier. Some of them are endemic, and others have been introduced. These plants hold a double function: one is the longitudinal distribution to cover the dune surface, and the other is the fixing capacity, or the capacity to consolidate the dune to a certain depth.

The main species present in the Pelluhue's dune barrier are:

- *Ammophila arenaria*: Commonly known as dune grass, has an extraordinary adaptability to Pelluhue's weather conditions. This plant has an extraordinary fixing capacity.

- *Lupinus arboreus*: This is an endemic species with a very good fixing capacity. This plant has a characteristic yellow flower that embellishes the dune field, and attracts insects for pollination.

- *Carpobrotus aequilaterus*: This endemic plant is known as "doca" in the local language. It is present in most of the dune areas in the seventh region of Chile where Pelluhue is located. This plant has an extraordinary capacity of longitudinal distribution, as well as a great fixing capacity.¹⁴⁹

¹⁴⁹ San Martin, Jose, Carlos Ramirez, Cristina San Martin: La flora de las dunas chilenas y sus adaptaciones morfológicas. Accessed February 20, 2013. <http://mingaonline.uach.cl/pdf/bosque/v13n1/art04.pdf>



Figure 92: Pelluhue Dune Barrier Species
 Source: Felipe Igualt 2014

B. Connectivity and Evacuation in Pelluhue Tsunami Forest

1. Connectivity

Pedestrian circulation is perhaps the most important mode of circulation in Pelluhue town. Most people don't have cars, and the distances in the town are not far and can easily be traversed by walking or biking. This thesis proposes a pedestrian walkway between the dune and forest to preserve the natural coastal environment, and to connect the main roads in the town with the dunes (beach access), forest, and river's edge. The pedestrian walkways also offer the accessibility for emergency vehicles.

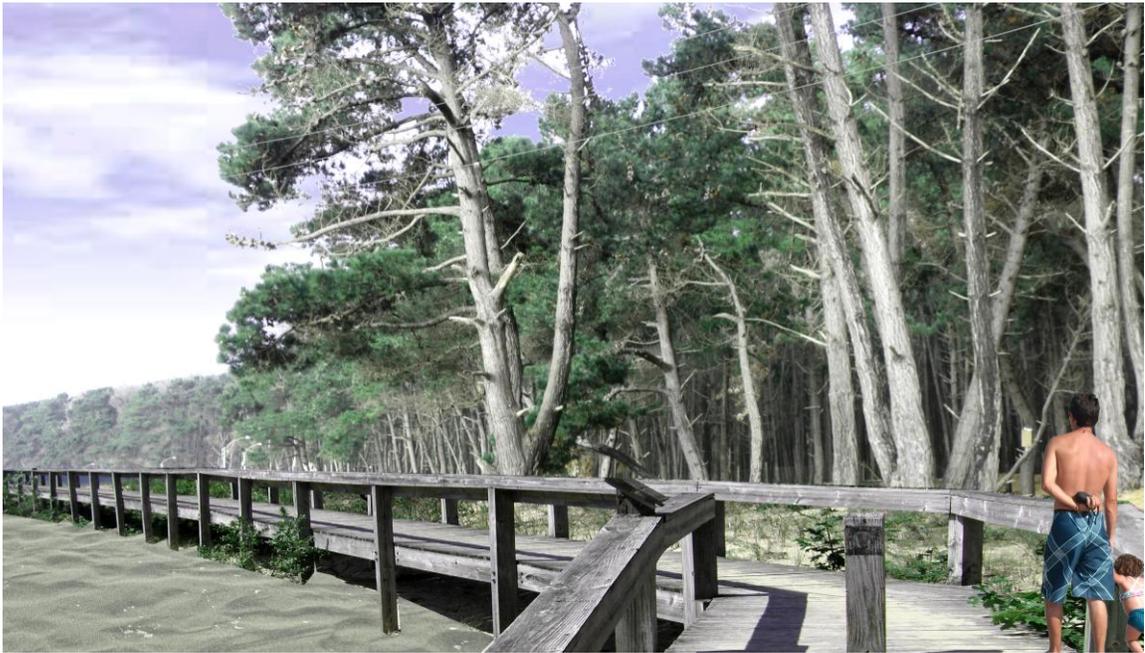


Figure 93: Elevated Dune Walkway
Source: Felipe Iguait 2014

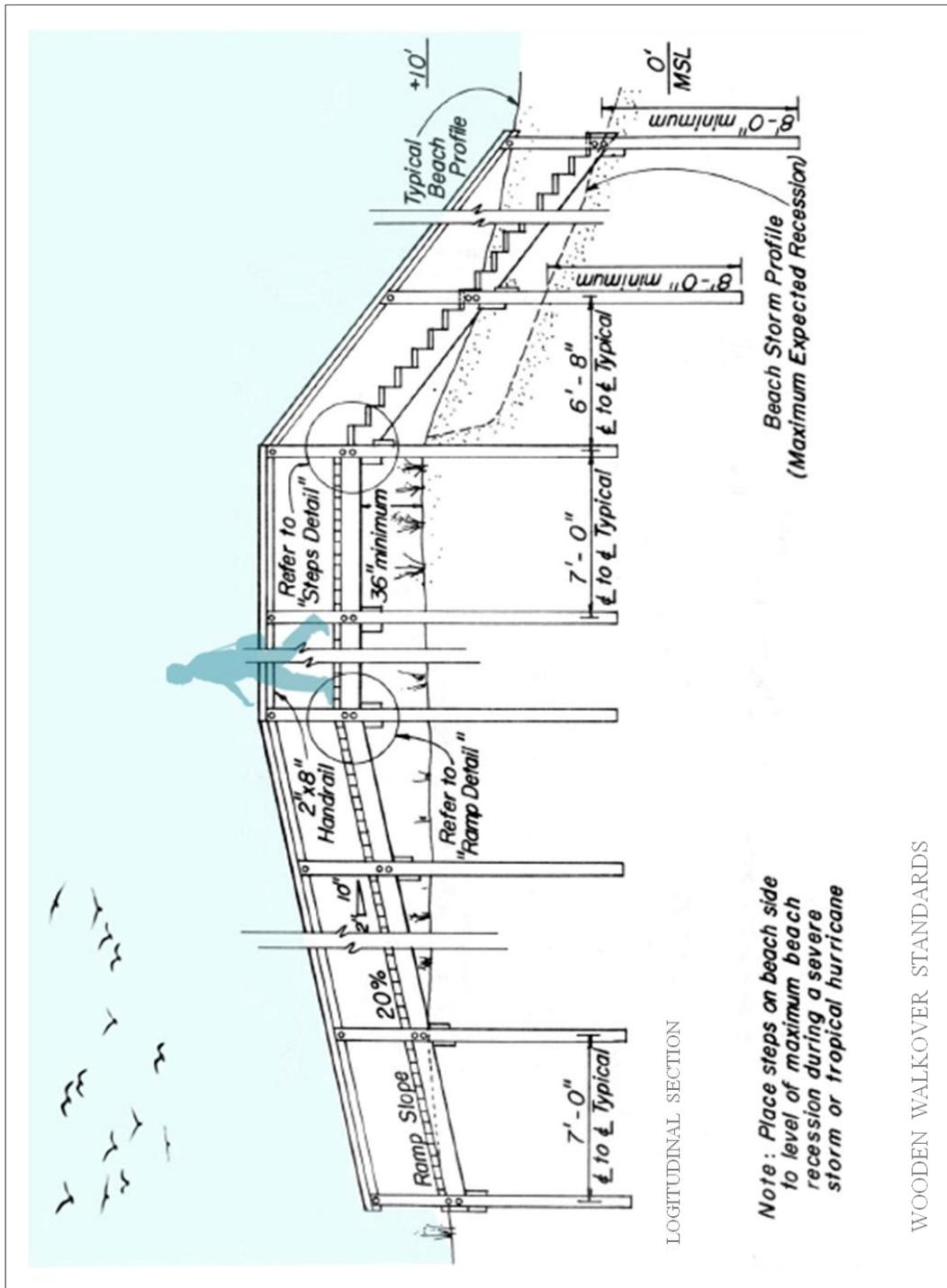


Figure 94: Wooden Walkway Standards
 Source: Florida Bureau of Beaches and Coastal Systems¹⁵⁰

¹⁵⁰ "Beach/Dune Walkover Guidelines," last modified January 20, 2014. http://www.fema.gov/media-library-data/20130726-1510-20490-1278/06_ccm_res_dunewalkover.pdf

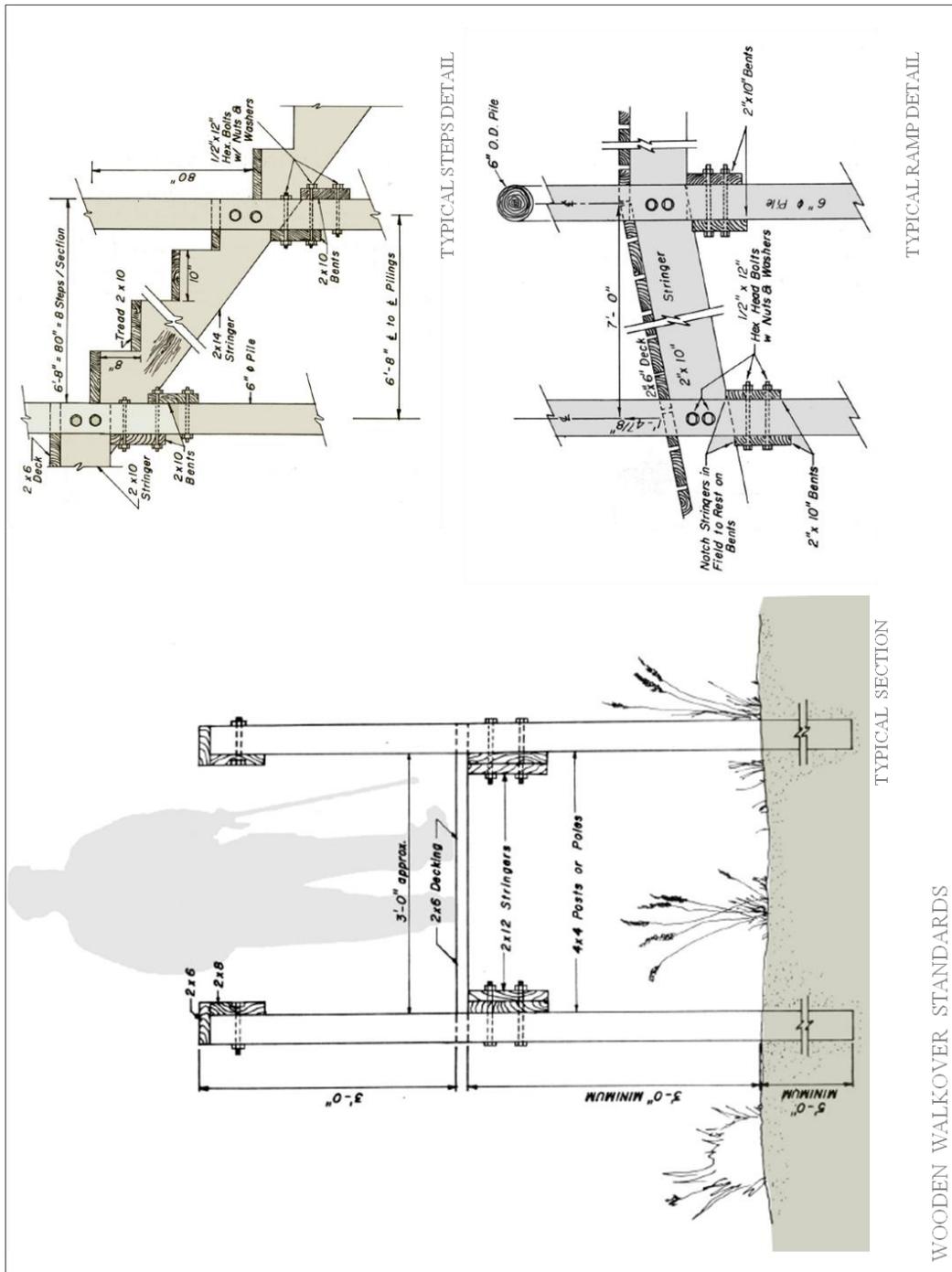


Figure 95: Wooden Walkway Standards
 Source: Florida Bureau of Beaches and Coastal Systems¹⁵¹

¹⁵¹ "Beach/Dune Walkover Guidelines," last modified January 20, 2014. http://www.fema.gov/media-library-data/20130726-1510-20490-1278/06_ccm_res_dunewalkover.pdf



Figure 96: Walkway Beach Access
Source: Felipe Igualt 2014

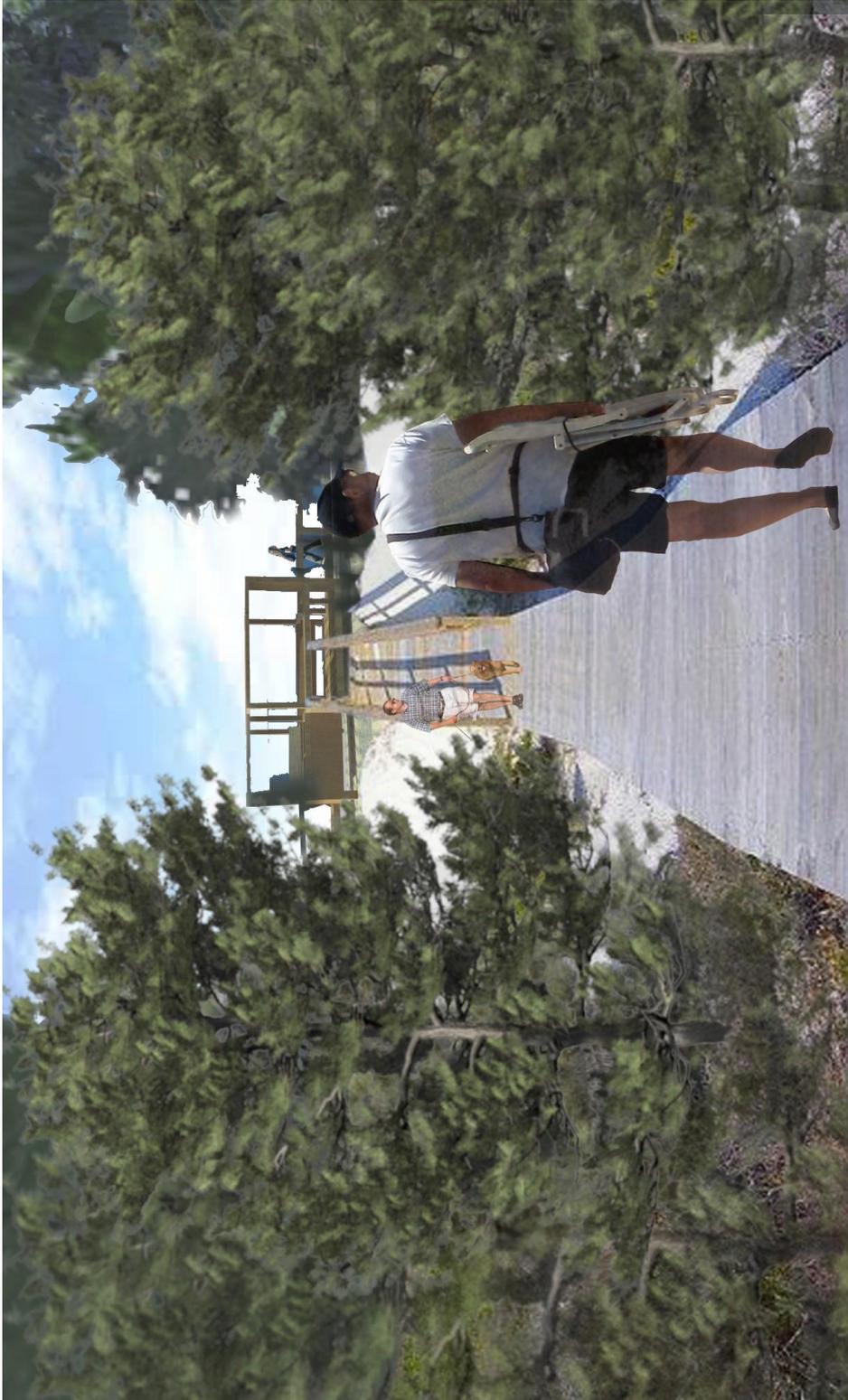


Figure 97: Walkway Forest Access
Source: Felipe Igualt 2014

The tsunami forest connects to the existing web of circulation in Pelluhue town with three secondary roads joining the beach with Abdon Fuentealba, the main road in Pelluhue town. The three roads are defined in this thesis as connectors. These roads provide a partial vehicular access to the forest, connecting the vehicular access with the pedestrian walkways.

The circulation within the dune barrier must protect the dune and plant species. For this reason, the proposed circulation and beach access is through an elevated wooden dune walkway. Damage to dunes from pedestrian traffic can be avoided by implementing these elevated walkover structures. This is a common solution to provide dune circulation; it is an inexpensive system, able to resist the weather conditions, and has a low to no impact on the landscape. Also, walkovers can contribute to an increase in public awareness of the importance of dune protection and appreciation of the natural environment.¹⁵²

¹⁵² "Coastal Dunes," Texas General Land Office, last modified February 20, 2013.
http://www.glo.texas.gov/what-we-do/caring-for-the-coast/_publications/DuneManual.pdf

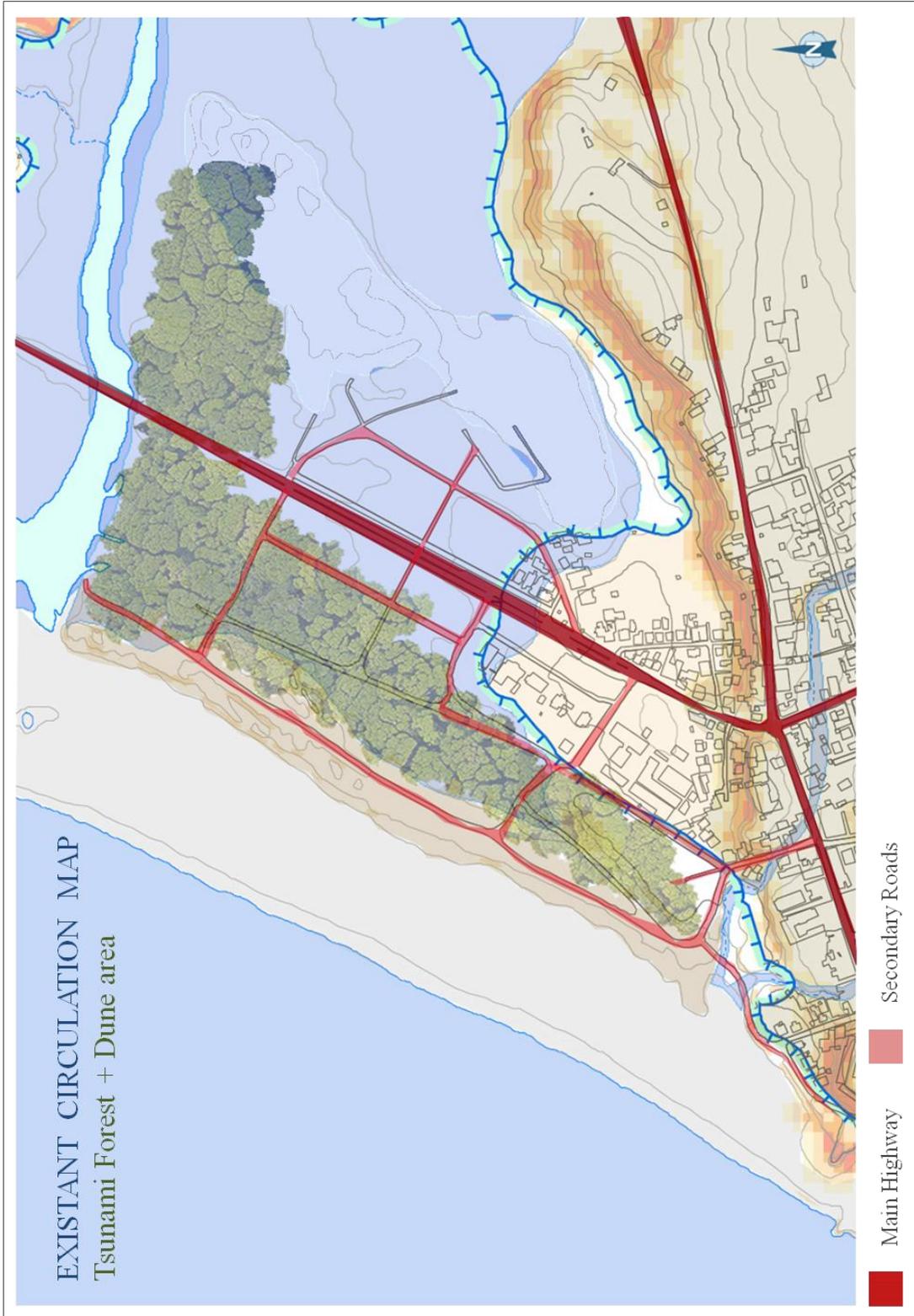


Figure 98: Existent Circulation Map
Source: Felipe Igualt 2014

2. Evacuation Plan

One of the most important components in any tsunami-susceptible town is an evacuation plan. An evacuation plan operates during times of emergency, and connects risk zones with safe areas in a reduced timeframe. These plans operate by pedestrian evacuation in order to avoid traffic congestion during emergencies.

After the 2010 tsunami in Chile, the Emergency office from the Chilean government ONEMI updated the evacuation map for each coastal locality in the country. These maps were based on the 2010 tsunami and historical data collected from localities where previous tsunamis reached a higher flood elevation. Today, any new building or landscape intervention (public or private) must meet the requirements of the official ONEMI evacuation plan.

There are three vehicular roads perpendicular to the beach connecting Abdon Fuentealba, the main road in the town, to the Pelluhue Tsunami Forest. These are part of the evacuation routes of the official evacuation plan. The three roads provide the link between the existing official evacuation requirements and the new defensive landscape proposed herein. The nearest safe area is located 1 mile from the river's edge. An average person takes 25 minutes walking from the northernmost location in the dune barrier to the nearest safe area.



Figure 99: ONEMI Pelluhue Evacuation Plan
 Source: ONEMI 2014¹⁵³ + Felipe Igualt 2014

¹⁵³ "Mapas de Evacuación por Tsunami, Región del Maule," ONEMI Chile, last modified April 20, 2014. <http://repositoriodigitalonemi.cl/web/handle/123456789/1664>



Figure 100: Pelluhue Tsunami Forest: Pedestrian Connectivity Plan
 Source: Felipe Iguait 2014



Figure 101: Pelluhue Tsunami Forest + Dune Barrier Evacuation Plan
 Source: Felipe Igualt 2014

3. Tsunami Forest Facilities

This design exploration work proposes to incorporate three way-stations into the pedestrian walkway circulation. These stations are located in the intersection between the pedestrian walkway and the connector roads. The way-stations are made of the same materials as the dune walkover, and incorporate educational and emergency information for public use. These stations also provide a water fountain, seating, protection from the sun and rain, and an emergency alert system.



Figure 102: Elevated Wooden Walkway
Source: Felipe Iguait 2014

4. Educational Components

Before the 2010 tsunami in Pelluhue County neither tsunami information, nor ecological information, was provided in a public space. Even though today there is information available about safe areas and evacuation routes, there is no public information regarding tsunamis or ecology for the coastal area. This design exploration incorporates these informational elements into the three stations along the pedestrian walkway. These stations will educate the residents as well as tourists who visit Pelluhue during the year. Each of these three stations provides different information and views depending on the location.



Figure 103: Educational Station South
Source: Felipe Iguait 2014

The first station, located nearest to the town, provides a view of the town and contains information about the tree species of the tsunami forest as well as 2010 tsunami information. The second is located in the center of the beach and provides information about dune preservation, dune plants, and endemic forest species, together with tsunami evacuation information. The third is located in the north side of the dune barrier intersecting with the river walkway. In this location the information is about the birds, riparian vegetation, and the evacuation plan. In this way, when the people walk through the pedestrian walkway, they will contemplate the beauty of the coastal environment, and learn how the natural elements (flora and fauna) help protect them from tsunamis.



Figure 104: Educational Station 2 Access
Source: Felipe Igualt 2014

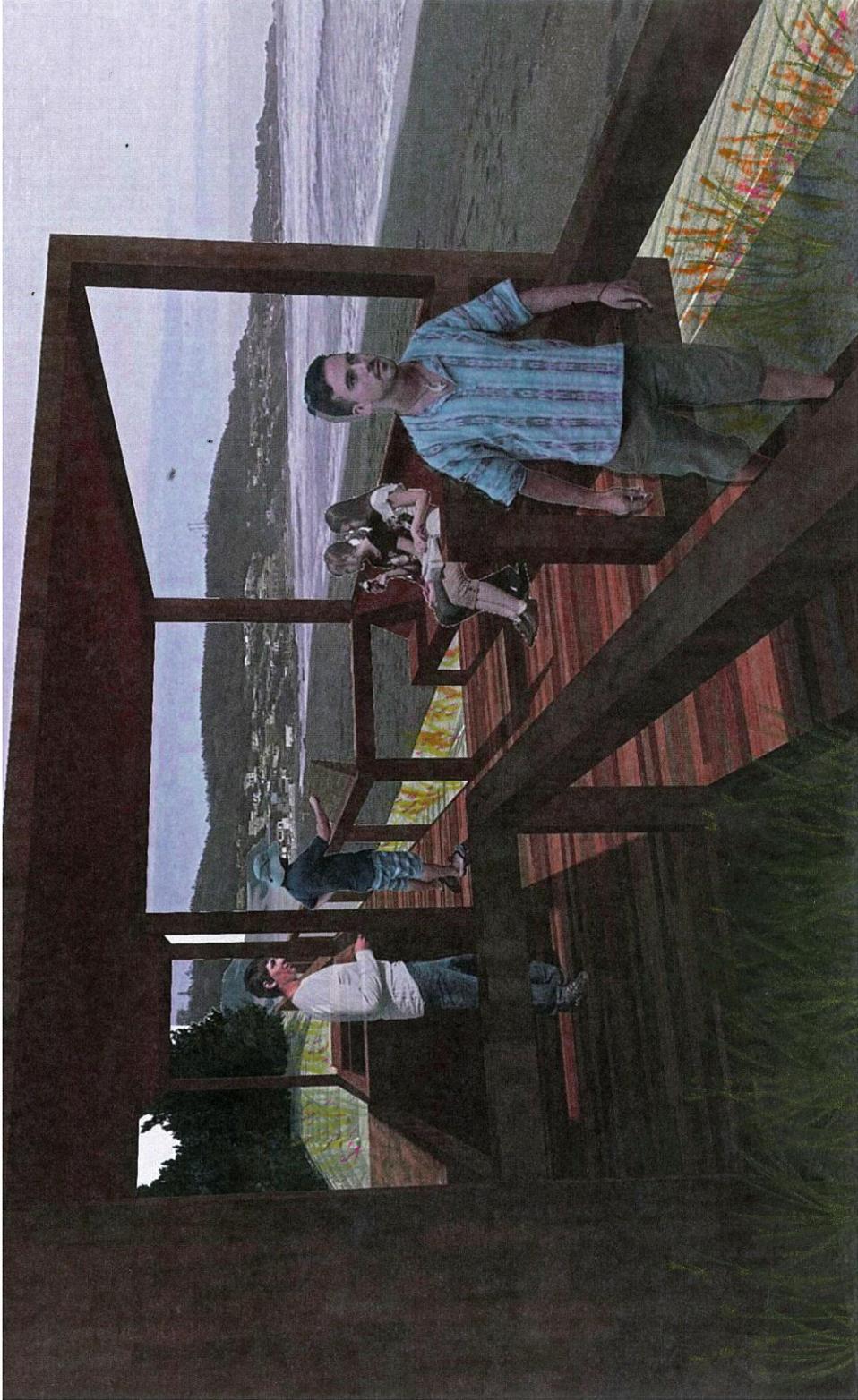


Figure 105: Educational Station North
Source: Felipe Igualt 2014



Figure 106: Dune Walkway + Educational Stations
Source: Felipe Igualt 2014



Figure 107: Dune Walkway + Educational Stations
Source: Felipe Igualt 2014

Conclusions

The development of Pelluhue County has been conditioned historically by its abrupt geography, which has limited the connectivity to and imports into the county. However, this singular geography also offers a wide variety of natural resources from which the community can use for their own food source. The good coastal weather and beautiful landscape add to the residents' high quality of life. The high productive potential of the waterfront can be understood through the historical and contemporary utilization of Pelluhue's seafront. However, the lack of infrastructure and connectivity creates difficulties in taking advantage of this productive potential.

The damage caused by the Chile 2010 earthquake and tsunami was mostly concentrated in the waterfront, with a higher degree of destruction in the river mouths of Curanipe, El Manzano, Curanilahue, and Mariscadero rivers. The tsunami flood damaged a large percentage of buildings and structures placed along the Pelluhue's waterfront. The nonexistence of mitigation elements allowed the direct impact of tsunami waves against the dwellings placed along the waterfront. At the same time, the lack of an evacuation plan increased the number of victims in the county.

In this thesis, the effectiveness of the most common artificial coastal defensive structures was evaluated in different tsunami scenarios. By analyzing the performance of them, it is clear that nature's forces are stronger than any structure trying to control them. However, by designing a strategic mitigation plan, which combines natural and artificial protective measures, together with a strategic evacuation plan, the degree of potential damage to Pelluhue County can be considerably reduced in the future.

Due to the lack of resources to build large-scale defensive structures against tsunamis, the tsunami forests are a realistic solution for Pelluhue County based on the advantageous soil conditions and low costs of implementation. Based on the data obtained in this research, a preliminary schematic design was developed for Pelluhue town, in order to visualize how a defensive green belt can take shape along the coasts of Pelluhue town.

The main benefits of tsunami forests are the reduction of the energy of a tsunami, increased ability to block floating debris, and the preservation of coastal ecosystems. Tsunami forests not only decrease the possibility of destruction, but also help to reduce coastal hazards such as blowing sand, salty wind, and high tides. The most relevant parameters in a tsunami forest are the forest width, tree density, age, tree diameter and height, and species composition. Due the complexity of these variables, the forests demand continuous and appropriate management into the future. Failures associated with forest design, such as forest gaps next to urban areas, tend to increase the potential of destruction.

Three main species of trees were reported as the most resistant in the central-south area of Chile after the 2010 tsunami. *Pinus Radiata* and *Populus Alba* were reported to have a very good performance during tsunami flood along the whole region. However, *Cupressus Sempervirens* was identified as the strongest species for Pelluhue County being able to support 14m (45ft) flooding in some areas.

A schematic design, together with an evacuation plan, was elaborated to visualize the beneficial factors of implemented mitigation interventions. From the design exercise it is possible to identify three main areas of intervention:

- a. The Beach + Dune area: In this area it is not only important to take care of the beach of Pelluhue (main source of sea food and touristic attraction) but also the growth and consolidation of the dune as a defensive barrier to mitigate tsunami energy.
- b. The Tsunami Forest: This area varies between 50 to 200 meters (150 - 600 ft), allowing to the forest the necessary density and width to be able to mitigate tsunamis. The front extension, in the beachfront reaches 750 meters (2300 ft).
- c. The Riverfront area: Since rivers are natural gaps with the highest potentiality for destruction during a tsunami, it is necessary to provide natural mitigation in this zone of the Pelluhue town. In this area the tsunami forest has the same extension as along the beachfront.

In each of these areas it is possible to designate specific plant and tree varieties.

Based on the geographical similarity with the other affected coastal towns in the central-south region of Chile, this thesis could be used as a model for other waterfront rehabilitation projects. This model can be reiterated by using the existing natural resources to mitigate tsunamis and storms, instead of the incorporation of large-scale concrete structures. Future research in this field may be focused in the tree species composition, as well as in the forest management over time, in order to have the forest meet the conditions to protect settlements from future tsunami floods.

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